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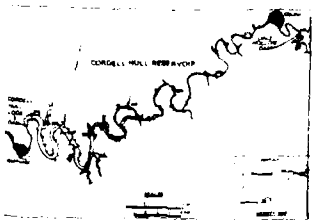
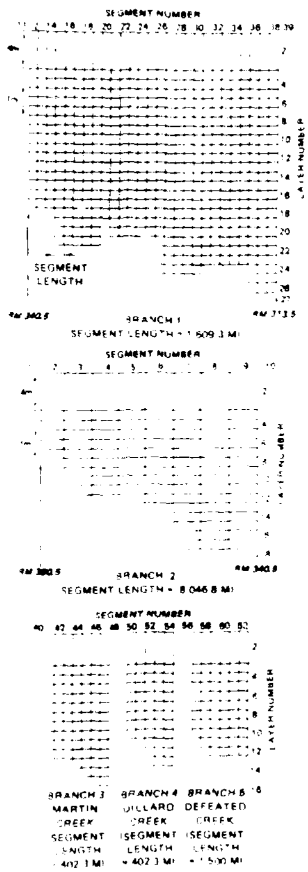
APPLICATION OF A TWO-DIMENSIONAL MODEL OF HYDRODYNAMICS AND WATER QUALITY (CE-QUAL-W2) TO CORDELL HULL RESERVOIR, TENNESSEE





by

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This report documents the application of a two-dimensional, laterally averaged, numerical model of hydrodynamics and water quality (CE-QUAL-W2) to Cordell Hull Reservoir, Tennessee. This reservoir is part of a system of Corps of Engineers-operated reservoirs in the Cumberland River Basin. Although not problematic within Cordell Hull Reservoir, unacceptably low dissolved oxygen concentrations farther downstream in the system of reservoirs have caused concern. This model study was undertaken as part of a potentially system-wide modeling effort to evaluate, without risking possible environmental degradation by experimentation at prototype structures, the water quality (specifically temperature and dissolved oxygen) impacts of operational changes at individual reservoir outlet structures.

Additionally, this particular study was designed to reveal the interactions between hydrodynamics and stratification within Cordell Hull Reservoir. Unstable stratification

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is thought to be responsible for two additional problems in this reservoir: the absence of an anticipated substantial fishery and a less than desirable amount of contact recreation. The concept of installing submerged weirs at the mouths of two of the reservoir's embayments within an established recreational site was proposed to help alleviate these two problems.

As Cordell Hull Lock and Dam operates as a run-of-the-river navigation project on the main-stem Cumberland River, no significant operational changes at this site are possible. The reservoir is characterized by high flows, intermittent moderate to weak thermal stratification, and a relatively shallow pool (maximum depth less than 25 m). These factors combine, as was demonstrated by the model testing results, to preclude significant control over the release quality characteristics. However, the advective nature of the reservoir presents an advantage. Any changes to the quality of incoming water of Cordell Hull Reservoir will be propagated downstream, largely intact. It was concluded, therefore, that changes in the quality of releases from the storage impoundments upstream of Cordell Hull Reservoir might impact the water quality a considerable distance downstream.

The hydrodynamics within the reservoir were found to be relatively insensitive to the degree of stratification. Thermal stratification was found to remain moderate to weak from the usual top-to-bottom withdrawal patterns in the reservoir. The results of testing with the proposed weirs were mixed, as anticipated. Placement of the weirs resulted in the desired stably stratified environment, but also permitted significant depletion of dissolved oxygen concentrations within the embayments.

The boundary condition input data are shown in Appendix A, and a sensitivity analysis performed on the data is described in Appendix B.

PREFACE

This report, sponsored by the US Army Engineer District, Nashville, as part of a numerical model study, documents the application of CE-QUAL-W2, a two-dimensional numerical model of hydrodynamics and water quality, to Cordell Hull Reservoir, Tennessee.

The study was conducted between March 1985 and January 1987 and the report prepared by Mr. Stacy E. Howington of the Reservoir Water Quality Branch (RWQB), Hydraulic Structures Division (HSD), Hydraulics Laboratory (HL), US Army Engineer Waterways Experiment Station (WES), under the direct supervision of Mr. J. P. Holland, Chief, RWQB, and Dr. R. E. Price, former Acting Chief, RWQB, and under the general supervision of Messrs. J. L. Grace, Jr., former Chief, HSD; G. A. Pickering, Chief, HSD; and F. A. Herrmann, Jr., Chief, HL. Invaluable assistance was provided by Mr. R. C. Berger, Jr., RWQB. Dr. J. L. Martin of the Water Quality Modeling Group (WQMG), Environmental Laboratory, and Mr. M. S. Dortch, Chief, WQMG, provided guidance in the modeling of dissolved oxygen. This report was edited by Mrs. Marsha Gay, Information Technology Laboratory.

COL Dwayne G. Lee, CE, is the Commander and Director of WES. Dr. Robert W. Whalin is the Technical Director.

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CONTENTS

APPLICATION OF A TWO-DIMENSIONAL MODEL OF HYDRODYNAMICS AND WATER QUALITY (CE-QUAL-W2) TO CORDELL HULL RESERVOIR, TENNESSEE

PART I: BACKGROUND

Project Description

1. Cordell Hull Reservoir is located in north-central Tennessee on the Cumberland River (Figure 1). It is impounded by the Cordell Hull Lock and Dam, which is maintained by the US Army Engineer District (USAED), Nashville, of the US Army Engineer Division, Ohio River. The dam, at river mile (RM) 313.5 (measured upstream from the mouth of the river), is the most upstream of the four navigation projects on the Cumberland River. It houses a run-of-the-river hydropower facility with three hydroturbines capable of producing a total of 100 MW. Releases from the structure are made primarily through the hydroturbines with a small amount of flow discharged through lockages. Excess

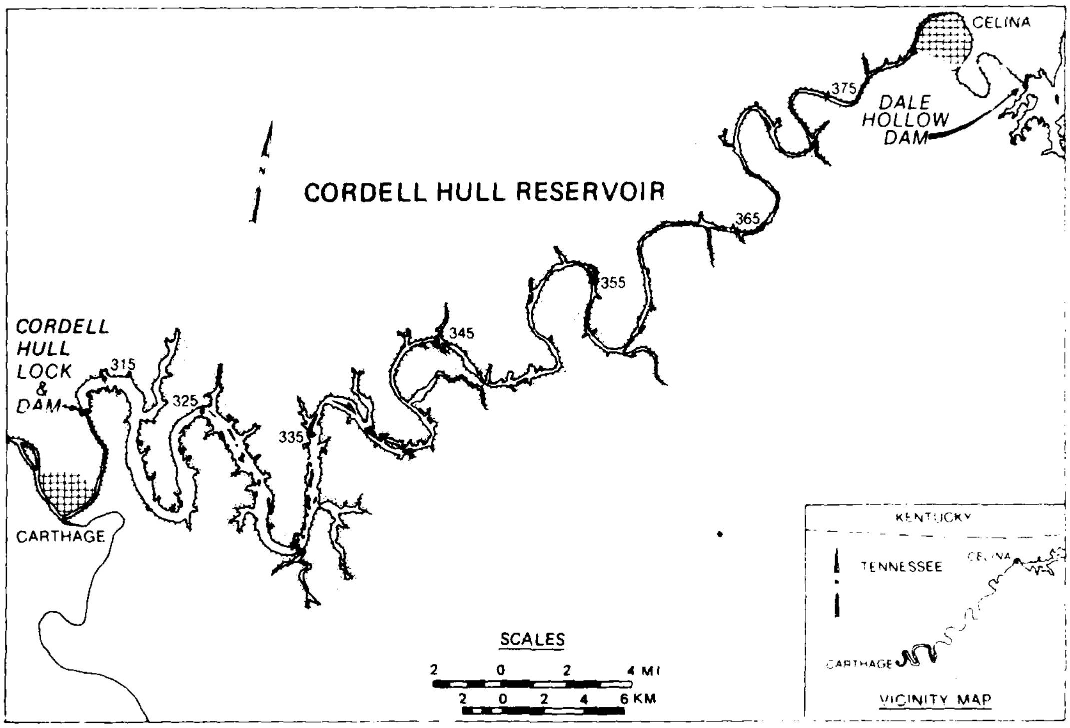

Figure 1. Cordell Hull Reservoir

flows pass over a tainter-gate-controlled spillway. The average flow through the project is approximately 3,680 cu m/sec. The storage at normal summer pool (el 153.6*) is about 0.32 cu km, which provides an average lake residence time of about 10 days. The depth of water at the dam is about 21 m at normal summer pool.

2. The reservoir is located in gently rolling terrain which is surrounded by moderately mountainous terrain common to the Cumberland Mountains of middle Tennessee. The area is wooded but has scattered open fields and scenic bluffs.

3. The lake is generally cold due to the hypolimnetic releases of two upstream storage impoundments: Wolf Creek Dam, which impounds Lake Cumberland, and Dale Hollow Dam, which impounds Dale Hollow Reservoir. Wolf Creek Dam is located at RM 460.9 on the Cumberland River in Kentucky, and Dale Hollow Dam is located at RM 7.2 on the Obey River which joins the Cumberland at the headwaters of Cordell Hull Reservoir at about RM 380.0. Cordell Hull Reservoir has a drainage area of 21,000 sq km, but 83 percent of the flow into Cordell Hull Reservoir comes from these two storage impoundments.

4. Cordell Hull Reservoir is about 116 km long with its headwaters near Celina, Tennessee. The lake is narrow and the steepness of the surrounding topography has allowed the reservoir to retain the sinuosity of the pre-impounded river. The reservoir has been in normal operation since 1973; however, no extensive water quality data base is available.

5. Immediately downstream of Cordell Hull Dam is Old Hickory Lake. A majority of the inflows to Old Hickory are provided from Cordell Hull Reservoir, with most of the remainder provided by the Caney Fork River, which joins the Cumberland River about 8 km downstream of Cordell Hull Dam at Carthage, Tennessee. About 32 km downstream of Old Hickory Dam is the city of Nashville, Tennessee.

Problem Description and Potential Solutions

6. Prior to impoundment of Cordell Hull Reservoir, the Cumberland River had good reaeration characteristics between RM 313.5 and RM 385 comparable to

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* All elevations (el) and stages cited herein are in metres referred to the National Geodetic Vertical Datum (NGVD).

most other free-flowing river reaches. The dissolved oxygen (DO) concentrations were usually at or near saturation as the flow entered Old Hickory Lake. Even so, significant degradation of the DO concentrations was possible during low flows through the Old Hickory pool. Impoundment of Cordell Hull Reservoir has turned this reach, which had been a source for DO, into a sink contributing to the DO problem in the Old Hickory releases.*

7. Low DO concentration is not the only problem associated with Cordell Hull Reservoir. Prior to impoundment, the reservoir was expected to develop and maintain a substantial coldwater fishery.* This fishery has not yet developed as expected. A suspected reason for this lack of development is the unstable thermal stratification in the lake. The lake can easily transform from a moderately stratified reservoir to one with very weak, if any, stratification. It can also restratify quickly. This type of environment is not conducive to warmwater or coldwater fishery development.

8. The unstable stratification patterns have also served to limit the amount of contact recreation on the reservoir. The lake is generally cold due to the cold inflows and low retention times, but during the summer months, the epilimnetic temperatures in the downstream reaches have reached levels adequate for comfortable contact recreation. The consistency of the warm epilimnetic temperatures is not guaranteed, however, due to the instability of the stratification.

9. The solutions to these problems are not obvious. However, since a large majority of the water in the Cumberland River at Cordell Hull Reservoir has passed through at least one Corps of Engineers-controlled structure, it was thought that operational changes at these structures might provide some improvement. To evaluate this potential for improvement, a more in-depth understanding of the dynamic stratification patterns in the reservoir and the physical circumstances which influence these patterns is needed. This understanding may be gained through the use of numerical modeling. A numerical model would allow the implementation of operational and physical changes and the evaluation of their relative impacts without disturbing the prototype.

10. One proposal for the improvement of the fishery and contact recreation has been the installation of submerged weirs at the mouths of some of the

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* J. K. Brown. 1984 (Nov). "Application of LARM to Cordell Hull Reservoir," Memorandum for Record, US Army Engineer District, Nashville, Nashville, TN.

tributaries. This would potentially decrease lower level exchange with the main reservoir and thereby warm these embayments for recreational use and warm-water fishery development. This proposal can also be evaluated by computer rather than in the prototype.

Purpose and Scope of Study

11. CE-QUAL-W2, a two-dimensional, laterally averaged, numerical model of hydrodynamics and water quality, was chosen to be applied to Cordell Hull Reservoir jointly by the Hydraulics and Environmental Laboratories of the US Army Engineer Waterways Experiment Station (USAEWES). The application involved model adjustment and verification against observed data for April through October of two historical years. The verified model was then used to simulate hydrodynamics, temperature, and DO within the lake for a wet, an average, and a dry April through October for the purposes of (a) developing a better understanding of the interactions between stratification and hydrodynamics in this reservoir; (b) evaluating the water quality impacts of proposed submerged weir placement; and (c) evaluating the effects of hydropower operations on reservoir water quality characteristics. This report documents the application process and the results of the study. A more detailed description of the model is available in its user's manual (USAEWES 1936).

PART II: MODEL DESCRIPTION

12. An evaluation of the dynamic thermal stratification in Cordell Hull Reservoir required investigation of the stratification patterns in both the vertical and longitudinal directions. Due to the relative narrowness and shallowness of this reservoir as compared to other reservoirs, no significant variations in the lateral direction were anticipated. Therefore, a two-dimensional laterally averaged model was recommended.

13. The model chosen for this application was CE-QUAL-W2, a two-dimensional laterally averaged model of hydrodynamics and water quality. CE-QUAL-W2 is a descendant of the Laterally Averaged Reservoir Model (LARM) (Buchak and Edinger 1982), and its descendent, the Generalized Longitudinal and Vertical Hydrodynamics and Transport (GLVHT) model (Buchak and Edinger 1984). CE-QUAL-W2 contains essentially the same techniques for resolving hydrodynamics and conservative transport as those which have been proven in over 20 successful, practical applications of the LARM and GLVHT models (Buchak and Edinger 1984). The most important difference between CE-QUAL-W2 and GLVHT is the addition of water quality simulation capabilities. The GLVHT model has been modified and extensive coding added to produce CE-QUAL-W2, a model that can simulate the interaction of several important water quality parameters (USAEWES 1986).

14. CE-QUAL-W2 uses finite difference techniques to approximate the solution to the partial differential governing equations. In all, six unknowns are sought from six equations:

- a. Free-surface wave equation
- b. Hydrostatic pressure
- c. Horizontal momentum
- d. Continuity
- e. Constituent transport
- f. Equation of state relating density and constituents

The solution technique is explicit with the exception of the water-surface resolution, which is implicit. This implicit solution avoids the restrictive Courant criterion that relates wave speed, grid spacing, and time-step and is often the most limiting requirement for computational stability.

15. Some simplifying assumptions were necessary in the development of the model to maintain its cost effectiveness for practical application. These

assumptions must be outlined and understood to avoid improper application. The two-dimensionality of the model requires that the results be averaged in the lateral dimension. Therefore, if substantial velocity or constituent gradients exist laterally which need to be represented by other than an average value, this model is an inappropriate choice.

16. The imposition of the solution on a fixed rectangular grid has some inherent assumptions. The variables are averaged within the confines of each cell. The grid divisions must be sufficiently small to represent any important gradients. The fixed rectangular nature of the grid means that slopes in topography are approximated by a series of stair-stepped rectangular cells. The grid is also assumed to provide an adequate representation of the reservoir morphology. The fineness of the grid is important in determining the adequacy of the geometric representation.

17. Another possible limitation is that CE-QUAL-W2 does not model turbulence. It employs eddy coefficients to represent the influences of turbulence. This assumption is very common among hydrodynamic models and should not measurably impact the results of this study. The hydrostatic approximation for pressure is also incorporated in this model. This greatly simplifies the equations, decreases the computational costs, and is a good assumption except in applications where substantial vertical acceleration occurs.

18. Simulation of biological and chemical parameters within a reservoir also requires certain assumptions. Obviously, not every particle and its interactions can be traced through a body of water. Therefore, a finite number of parameters are employed to represent the system's behavior. The modeling processes and a detailed listing of the water quality constituents are given by USAEWES (1986).

PART III: MODEL APPLICATION

19. The application of a numerical model of this nature requires that several preparatory steps be taken. These include the development of a numerical grid, boundary and initial conditions, and a stable, yet reasonable time-step size. The geometry and water budget must also be evaluated prior to model adjustment. The decisions described in the following paragraphs represent the final product and do not always reflect the steps undertaken to arrive at these decisions.

Grid Development

20. Initially, the model limits within the lake had to be established. The decisions concerning grid development required close coordination between USAEWES and the Nashville District. The downstream limit of the model was established at RM 313.5, which is the location of the dam. The upstream limit was located at RM 380.5, which is near the Highway 52 bridge at Celina, Tennessee, yet below the confluence of the Obey and Cumberland rivers. A flow gaging station located at this bridge provided necessary flow data at the upstream end of the model.

21. The sizes of the computational cells (rectangular divisions in the vertical-longitudinal plane) were then computed. Since only one value of velocity, temperature, and each water quality constituent may be used to represent the entire volume enclosed by these imaginary cells, the cells need to be smallest in the areas with the largest variable gradients. In this case, good resolution was desired in the area closest to the dam, but was not necessary in the upstream areas. Since only one cell length (segment length) is allowed per branch by the model, the region to be simulated was divided into two branches. The reach downstream of RM 340.5 was declared branch 1. The reach from RM 340.5 to RM 380.5 at Celina was declared branch 2. The vicinity of RM 340.5 was chosen because it is located in a large bendway (Smith's Bend) and the longitudinal momentum along the axis of the reservoir should be small. The numerical model will not advect momentum at the juncture between the branches. The cells in branch 1 were made 1.61 km long to better resolve the stratification gradients in this reach, while the cells in branch 2 were made 8.05 km each.

22. Vertical dimensions of the cells also had to be declared. This dimension is not variable with each branch. The original CE-QUAL-W2 model required that all cells be the same height (same layer thickness). However, the model was modified to allow specification of two-layer thicknesses similar to that in Berger.* This was determined to be necessary due to the potentially large slope of the water surface. The model does not allow the water surface to span more than two layers at any one time. Therefore, a thicker surface layer was needed to allow large water-surface slopes during higher flow periods while maintaining the vertical resolution over the rest of the pool depth. The cells were made 1 m thick except at the surface where they were 4 m thick. This did not greatly reduce the resolution in the top layer as the water depth in this thick layer was usually small.

23. The reservoir volume is largely resident in the main stem, but some of the tributaries appeared to store significant amounts of water. Other than the main stem, which is composed of branches 1 and 2, three branches were defined: Martin Creek (RM 333), Dillard Creek (RM 332), and Defeated Creek (RM 317). The volumes of these branches appeared to be substantial enough to influence the main-stem modeling due to side channel storage. For modeling the main stem, the branch volumes were important, but a detailed bathymetric description was not required. The Martin and Dillard embayments were actually composed of two tributaries each. However, to conserve computational time, which increases significantly with the addition of each branch, the tributaries within each embayment were volumetrically combined to form an approximation of the Martin and Dillard embayments. These embayments were named branches 3 and 4, respectively. The vertical discretization in these branches was the same as the main stem, but the segment lengths were established at 0.4 km. This was done to allow these short tributaries to be included while not violating the model's lower limit on the number of segments necessary to define a branch. For Defeated Creek, branch 5, the segment length was established at 1.50 km and the vertical discretization was defined the same as the other branches. The resulting grid is given in Figure 2.

24. Other tributaries which contributed flow to the system without contributing substantial side channel storage volumes were Roaring River (RM 358)

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* R. C. Berger. 1985. "Improvements to GLVHT4," Memorandum for Record, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

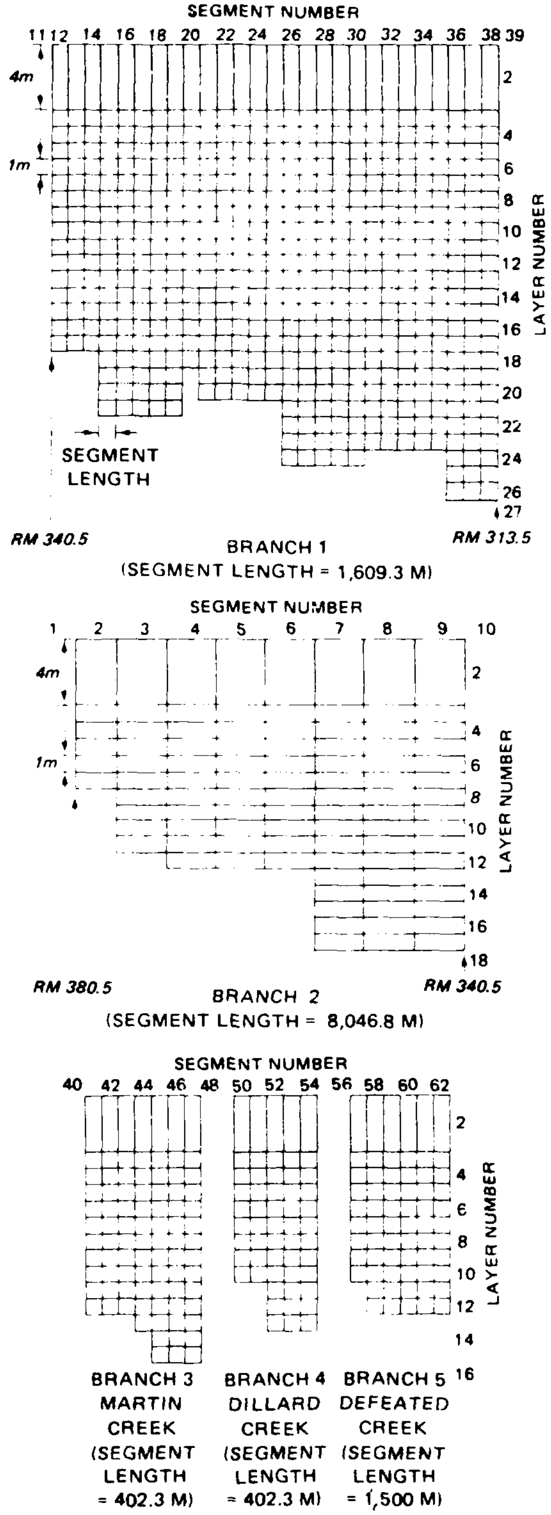

Figure 2. Numerical grid for main-stem simulation

and Jennings Creek (RM 355). These were declared as tributaries which required no geometric description in the model. Only discharge, constituent concentration, and segment of entry were required for tributaries. The remaining tributaries were grouped into a distributed tributary term for which flow was distributed among the segments within the branch based on surface area.

25. Bathymetric data are needed to make the numerical grid represent the lake volume. Required are widths at specified elevations which correspond to the tops of the layers at each segment. Cross-section data were provided for branches 1 and 2 at arbitrary intervals along the reservoir by the Nashville District. These cross sections were then interpolated using the US Army Engineer Hydrologic Engineering Center (USAEHEC) program GEDA (Geometric Data) (USAEHEC 1981) to provide data at the desired longitudinal locations and at the desired elevations. The bathymetry data for branches 3, 4, and 5 were extracted by hand from topographic maps of the region. Linear interpolation between the contour intervals was necessary to produce widths at the appropriate elevations.

Boundary and Initial Conditions

26. Conditions at each model boundary must be specified to resolve the previously outlined governing equations. These boundaries are the water surface, the upstream and downstream ends of each branch, and any inflow or outflow points along the reservoir. Meteorology affects the reservoir across the water-surface boundary. Meteorological data needed are solar radiation, coefficient of surface heat exchange, equilibrium temperature, and wind speed and direction. Daily averaged values of the coefficient of surface heat exchange and the equilibrium temperature were provided by the Nashville District as computed from the Nashville weather station located at the Nashville Airport, which is about 69 km west of the dam. Solar radiation was computed using the HEAT program (USAED, Baltimore, 1977) from air temperature, cloud cover, dew point temperature, and wind speed. These data were computed on a daily averaged basis from data obtained from the Meteorological Support Group at Scott Air Force Base, Illinois, for the Nashville Airport weather station.

27. CE-QUAL-W2 allows specification of either a water-surface elevation or a discharge boundary condition at each end of a branch. For this

application, flow was gaged at each end of the model limits. Therefore, discharge was specified at each end of the modeled reach. Branch 1 had zero external flow specified at the upstream end and the given discharge from the structure specified at the downstream end. The upstream branch, branch 2, had inflow specified at the upstream end (RM 380.5) and an internal head boundary specified at the lower end. An internal head boundary, when specified between branches, simply means that the flow from the upstream branch (branch 2 in this case) to the downstream branch (branch 1) is dictated by the water-surface elevation in the downstream branch at the location of the juncture between the branches.

28. Inflow quality specification was also necessary. Temperature and DO were routed from Wolf Creek Dam to RM 380.9 by the Nashville District using a statistical program, 401STR.* The Dale Hollow Dam releases join the Cumberland River at approximately RM 380.9. The quantity and quality of these releases were known at the dam, but the changes as the flow traveled 11.6 km to the Cumberland River were not known. It was assumed that the travel time for discharge was negligible and that the temperature increased by 1° C for all flow and meteorological conditions, based on memoranda from the Nashville District.* The upstream gaging station included the flow contribution from Dale Hollow Lake, but the Nashville District-routed quality did not. Therefore, the upstream inflow quality provided by the Nashville District was adjusted on a flow-weighted basis to include the Dale Hollow contribution.

29. The inflow quantity and quality had to be specified for each of the tributaries and for each of the remaining branches (3-5). The only gaged flow data on other than the main stem were on the Roaring River. The Roaring River and Jennings Creek tributary inflow quantities were approximated using a common drainage area ratio technique (Bruce and Clark 1966). The drainage area above the flow gage on the Roaring River was approximately 455 sq km. The entire drainage area for the Roaring River was 689 sq km. Therefore, the gaged discharge was multiplied by 689 and divided by 455 to provide an estimate of the total Roaring River inflow to the reservoir. Travel times were neglected in this process. This procedure also assumed that the precipitation amounts and runoff characteristics of each of the reservoir inflow points

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* J. K. Brown. 1985. Unpublished data, US Army Engineer District, Nashville, Nashville, TN.

specified were the same as for the known region on the Roaring River. Branches 3-5 and the distributed tributaries were treated in the same manner. Inflow quality also had to be specified. No water quality data were available for these inflows. Estimates of the inflow temperature and DO concentrations were provided by the Nashville District. The temperature and DO were specified as shown in Appendix A.

30. Downstream, the total discharge must be specified as well as the flow distribution if more than one layer of withdrawal is required. For this application, the release device most commonly used was the hydropower intake. The intakes for the hydroturbines are shown in Figure 3. These intakes spanned several layers vertically, and individual discharges for the layers had to be provided. Nashville District tests (USAED, Nashville, 1980) indicated that the downstream section produced a relatively constant discharge profile regardless of flow or stratification. This was probably an accurate assumption based on the size of the intakes and the usually large flows. The zone of withdrawal (Bohan and Grace 1973) intersected both the bottom of the reservoir and the water surface under virtually all operating conditions. In the Nashville District report, the numerical model SELECT was used in the verification of this assumption. Although the SELECT version used by the

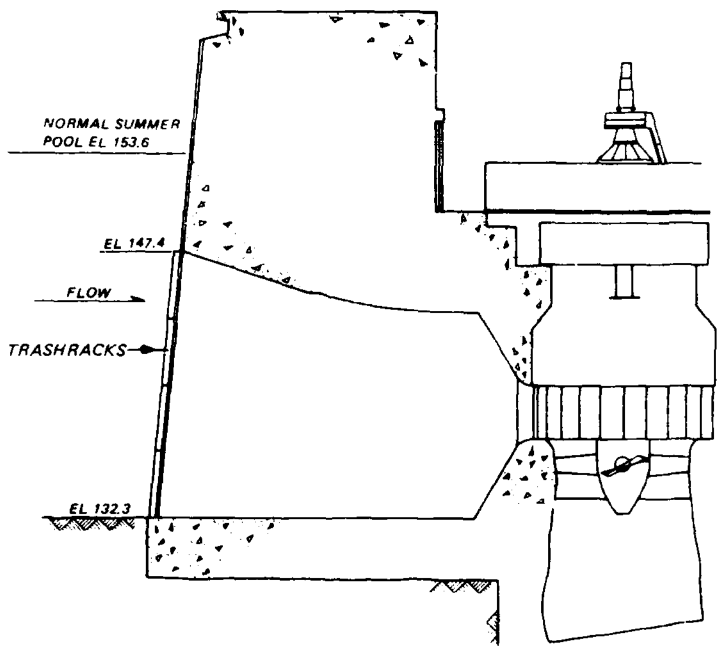

Figure 3. Hydropower intakes at Cordell Hull Reservoir

Nashville District assumed zero velocity at the boundaries of interference (which is no longer an assumption in the model), the results should not have been dramatically different from results using the more recent version. Thus, the percentage of the total discharge was established for each of the layers based on the profile computed by the Nashville District.

31. The initial conditions selected were 10° C and 10 mg/ℓ DO. The entire reservoir was assumed to be homogeneous on 1 April of each year simulated. The impacts of the selection of initial conditions were found to be negligible after only a few weeks of simulation as detailed in Appendix A.

Time-Step

32. The time-step was originally estimated by cell volume displacement. This concept simply means that an imaginary fluid particle cannot traverse a model cell either longitudinally or vertically within one time-step. This is not usually the controlling factor for time-step evaluation but gives a first estimate. The maximum vertical momentum diffusion is computed within the model based on time-step. Therefore, if the time-step is too large, inadequate momentum diffusion may result, which can lead to local temperature and density inversions. If this situation arises, a reduction in the time-step will cause an increase in the maximum allowable vertical diffusion and a smearing of the inversions, yielding stable vertical temperature and density patterns. The time-step selected for this application was 300 sec, except in cases where inadequate diffusion occurred; 200 sec was used as a time-step in these cases.

Geometry

33. The evaluation of geometry included reservoir volume and surface area comparison. The Nashville District* gave estimates of the volume and surface area of the Cordell Hull Reservoir at maximum normal summer pool elevation (153.6) and minimum normal pool elevation (152.1). The model-computed values of volume and surface area were then compared to the observed values.

* US Army Engineer District, Nashville. "Cordell Hull Lake, Cumberland River, Tennessee," pamphlet, Nashville, TN.

The geometric description, based on these comparisons, was considered acceptable.

Water Budget

34. Observed water-surface elevations were then compared to those predicted by the model. The Chezy coefficient was used to represent the roughness of the bottom of the reservoir which, along with discharge, determined the slope on the water surface. Daily readings of water-surface elevation were given at the dam. However, to evaluate the observed slope, another point of reference in the reservoir had to be used. Additional water-surface data at RM 357 were obtained from the Nashville District for a 2-week period in August 1981. The Chezy coefficient was then varied and the surface slope evaluated. The coefficient which provided the best results was 35 $m^{1/2}$/sec.

35. With the slope established, the water-surface elevations were evaluated. During the first period tested with 1979 data, the predicted water surface was consistently below the observed values. However, during other periods of the year, the predicted water surface was too high. No drainage area ratio existed which would make the given inflows and outflows provide the correct water-surface elevation. Evaluation of the observed data showed that at the end of one 31-day period (30 June (midnight) through 31 July 1979), the water-surface elevation was the same as when the period began (el 153.6), but the inflow (excluding any tributary flow) averaged 317 cu m/sec larger than the outflow for that period. Thus, the observed water surface should have risen substantially as predicted in the model.

36. The Nashville District was consulted about the water budget problem. The District indicated that, of the three parameters, water surface, inflow, and discharge, the inflow was the most likely candidate for adjustment.* The inflow gaging station is based on a slope-discharge rating curve and is probably not as accurate as the other two parameters. Therefore, the drainage areas were established including one designated area to represent lateral inflow from small, ungaged streams and precipitation on the water surface. The main-stem inflow was computed on a daily basis such that the model

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* Personal Communication, 20 Aug 1986, from J. K. Brown, Nashville District, Nashville, TN.

provided the proper water-surface readings. The inflow computations were based volumetrically on a water surface with no slope. Therefore, the predicted and observed values for water surface at the dam did not match exactly, but were within a reasonable range of accuracy (usually 0.3 m). This accuracy was good considering the free water-surface slope during simulations and the peaking nature of the releases.

37. The addition of variable-layer thickness capability appeared to cause occasional instabilities in the model. These instabilities were encountered when the water surface moved from one layer into another. These instabilities were overcome by using constant widths within each segment for each of the layers among which the water surface moved. This procedure required that for each individual segment, layers 2, 3, and 4 had the same width specified in the bathymetric input. A posttesting evaluation of this problem revealed a minor coding error which, when corrected, eliminated this need for uniform layer widths. The entire testing sequence was, however, not rerun as this change proved to have little impact on the results.

PART IV: MODEL ADJUSTMENT/VERIFICATION

38. Adjustment is the modification of specified model parameters to provide adequate correlation between the model and prototype data. The absolute best correlation is seldom, if ever achieved, as the process is generally discontinued when the fit is deemed adequate based on experience or statistical evaluation of the results. The model is considered to be verified when the model-to-prototype correlation is satisfactory. For this application, the temperature and DO profile data were used to evaluate the adequacy of the predictions.

Hydrodynamics and Water Temperature

39. Since hydrodynamics can only be directly adjusted using observed reservoir velocities, which were not and are seldom available, the thermal structure of the reservoir was used to fine-tune both the hydrodynamics and the thermal exchange and distribution coefficients. This is a very common practice and historically produces a well-adjusted model for both hydrodynamics and temperature.

40. The year 1979 was chosen as the year for adjustment due to the relatively large amount of profile data. Most of the adjustment was performed using the variables β and γ, where β is the fraction of incident solar radiation absorbed in the top 0.61 m of the water column, and γ is a coefficient controlling the exponential distribution of the remaining thermal energy through the vertical water column. It was estimated that β should be about 0.65 and γ should be about 0.9 (USAEWES 1986). Simulations were performed and predicted temperature profiles compared to observed data. The model results at the second interior segment downstream (segment 37, which is just upstream from the dam) were compared to the observed data at RM 314.0. Although the first interior segment (segment 38) was more appropriate geographically, the numerical boundary effects made the second segment a better choice for comparison. The comparison revealed predicted epilimnetic and metalimnetic temperatures consistently higher than in the observed data.

41. A sensitivity analysis was performed using the input data for the spring of 1979. This period was selected as a typical seasonally high flow period from which information regarding the advective nature of the reservoir

might be obtained. More detailed results of this analysis are given in Appendix B. From this analysis, the thermal structure in the lake appeared to be less sensitive to the traditional adjustment coefficients regarding thermal influx, wind shading, and longitudinal dispersion. The outlet description, inflow qualities, and fixed meteorological input had a more dramatic effect on the temperatures. The inflow quality data provided by the Nashville District* through statistical modeling were evaluated. The routings had taken place from Wolf Creek Dam (RM 460.9) 108 km downstream to RM 393.7, which was a water quality monitoring station, and from Wolf Creek Dam to RM 381.0, which was immediately upstream of the confluence of the Obey and Cumberland rivers. The predicted and observed values were compared at RM 393.7. The discrepancies in temperature for 1979 are plotted against Julian day in Figure 4. These discrepancies were included in the input by applying the same correcting temperature to the full routing (RM 460.9 to 381.0) as would have been needed in the shorter routing (RM 460.9 to 393.7) to produce the observed temperatures at the water quality monitoring station. When simulations were

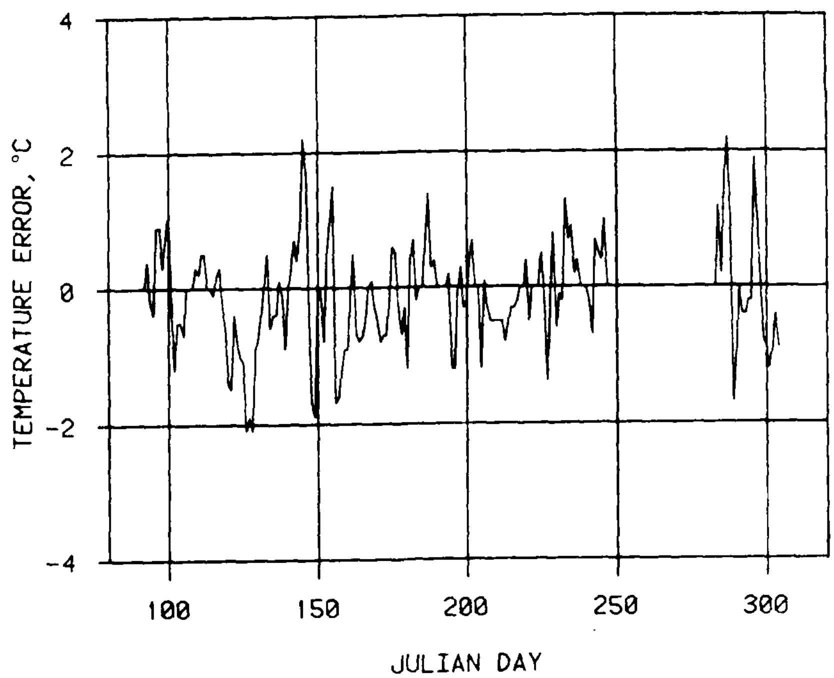

Figure 4. Statistical routing errors for temperature, 1979

* J. K. Brown. 1985. Unpublished data, US Army Engineer District, Nashville, Nashville, TN.

performed with these adjustments, the comparisons between the observed and predicted profiles improved noticeably, but not enough.

42. The outlet description was reevaluated. Several alternative methods of defining the release distribution were examined. The method that produced, statistically, the best fit between the predicted and observed profiles was a uniform velocity distribution at the downstream boundary. The predicted surface water temperature was, however, still too warm for each profile examined.

43. The meteorological input was also reexamined. According to Brown* and Brown,** the conditions at the Nashville Airport, where the meteorological data were originally collected, were considerably different from those on the water surface of Cordell Hull Reservoir. A heavy fog bank often sets up on the reservoir which may not dissipate until 9 or 10 a.m. on many days and can reestablish early in the evening. Further, the wind on the reservoir is usually calm. A report by Troxler and Thackston (1977) indicates these same tendencies from studies at nearby sites. The report documents the comparison between the meteorological data collected at the Nashville Airport weather station and those collected on the Cumberland River and below Center Hill Dam, which is on the Caney Fork River about 22.5 km southeast of Cordell Hull Dam. The results of their study indicated that the wind speed and air temperatures from the airport weather station often significantly exceeded the values at the study site. They concluded that the microclimate at the airport was substantially different from that on the river about 80.5 km away.

44. Another consideration involved herein is the portion of water surface of Cordell Hull Reservoir which receives direct sunlight. Due to the steeply sloping, meandering, tree-lined banks, some of the water surface of the reservoir is shaded for many of the daytime hours. The heat influx is probably reduced somewhat by this shading.

45. A small amount of temperature data were found from the Cordell Hull Dam, but not enough information existed at this site to compute solar radiation, equilibrium temperature, or coefficient of surface heat exchange. These data indicated that the air temperatures at the Cordell Hull Dam were

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* Personal Communication, 3 Oct 1986, from J. K. Brown, US Army Engineer District, Nashville, Nashville, TN.

** Personal Communication, 3 Oct 1986, from R. T. Brown, Tennessee Technological University, Cookeville, TN.

consistently substantially lower than the data collected at the Nashville Airport weather station. Based on this information, it became obvious that the meteorological data from the Nashville Airport were often unrepresentative of the Cordell Hull microclimate. Unfortunately, the existing data from the project were too sparse to allow quantification of the changes needed to transform the airport data into values more representative at Cordell Hull. Thus, to maintain the simplicity of the adjustment, the equilibrium temperatures and wind sheltering coefficients were the only changes to the input. The equilibrium temperatures were adjusted on a monthly basis. The changes that provided the best correlation between predicted and observed temperature profiles for the adjustment phase were as follows:

Month	Equilibrium Temperature Reduction, °C
April	3.0
May	3.5
June	4.0
July	4.0
August	3.0
September	2.0
October	0.0

46. The possible values for the wind sheltering coefficient range from 0, which is no wind, to 1, which means the full wind speed is applied in the computation of wind-induced mixing. The values decided upon were 0.3 for the main-stem branches and 0.2 for the side channel branches to coincide with the low wind speeds observed at the reservoir. These values were obtained purely by estimation of the impacts of the meandering nature of the reservoir, the topography, and vegetation on the wind speed at the water surface.

47. When the simulations were performed with the meteorological adjustments, the correlation was much improved. The water-surface temperature predictions were much closer to the observed values than before. However, the shape of the profiles, especially the location of the thermocline, was not accurate. The shape of the temperature profiles appeared to have been better with the original outlet configuration, which consisted of a constant, nonuniform discharge distribution among the layers. The provided discharge profile (USAED, Nashville, 1980) was then used with the adjusted inflow qualities and

meteorological conditions. The resulting correlation was significantly improved. Comparisons to observed data were deemed adequate, and the temperature adjustment was concluded.

48. The temperature verification results (con   isons following the final model adjustments) are given in Plates -6. For each of six locations in the lake, temperature versus depth is shown at seven different tim s during the simulation period. The overall comparison between the observed and numerically predicted temperature profiles was good. The only significant deviations occurred in the upstream region where inflow temperature dominated. Any error in inflow temperature was very pronounced at the upstream observation stations. The time of day of the comparison was also important. The model results reflected daily averaged values while the observed measurements could have varied greatly over the course of one day. Most of the deviations due to this consideration would have been seen near the surface.

Dissolved Oxygen

49. DO modeling was performed in conjunction with the Environmental Laboratory at USAEWES. DO is a primary consideration in water quality evaluation and can be interdependent with several different parameters. Modeling of DO can, therefore, take on various degrees of complexity. For this application, a labile dissolved organic matter (DOM) zeroth-order decay was used.

50. DO modeling required slight modifications to the model input used in the hydrodynamics and temperature adjustment phase. The only additional data required were DO concentrations for all inflows, a maximum DOM decay rate, and coefficients for the rate multiplier term which adjusts the decay rate based on temperature. Inflow DO concentrations, which had been statistically routed to RM 381.0, were adjusted for the errors in comparison with the RM 393.7 water quality station, as in the temperature adjustment. The inflow DO was also adjusted for Dale Hollow Dam release DO concentration. The DO measured in the Dale Hollow Dam releases was used at the upstream boundary by determining the percent contribution made by the Obey River to the total inflow and adjusting the DO appropriately based on a flow-weighted approach.

51. After the initial simulations, the predicted DO levels for the metalimnetic and epilimnetic regions of the lake were lower than those

observed in the reservoir for many of the observation days and stations. An evaluation of the saturation levels in the observed data indicated that supersaturation existed for much of the reservoir on many of the observation days. Also, the observed DO concentrations within the reservoir were considerably higher than the inflow concentrations had been for a considerable time prior. The DO concentrations actually appeared to have increased, on several occasions, as the water passed through the reservoir. Therefore, it was concluded that a source of DO must have existed in the reservoir. The most reasonable theories were high tributary inflow DO and photosynthetic oxygen generation.

52. The tributary inflow DO concentrations were artificially raised to 14 mg/ℓ and the simulations performed again. Only a minor increase was observed in the DO concentrations in the main stem. The amount of flow contributed by the tributaries, although relatively high during this period compared to other periods, was still only a small percentage of the flow in the main stem. Therefore, any change in constituents in the tributary inflow would have only slightly impacted the main-stem reservoir water quality.

53. Another possible explanation for the increase in DO within the reservoir was photosynthetic oxygen generation. Highly oxygen-supersaturated water has been observed when algae are present (Wetzel 1975). These saturation levels are obtainable through the model by simulating algae and its interactions with other constituents. However, more inflow constituent data were required to adequately represent algae than were available from this reservoir. For the type of DO modeling used in this application, which was chosen based on the types and amounts of data available, the only sources of DO were surface exchange and inflow. Surface exchange would, however, have driven supersaturated surface water toward saturation. Further, supersaturation could have been achieved from nonsupersaturated inflows by increasing water temperature. If coldwater inflows were not allowed to degas as the temperature of the water increased, as with an underflow, the saturation level would have increased. However, the concentration levels would not have increased as the observed data showed, only the percentage of saturation.

54. The observed data furnished by the Nashville District revealed significant supersaturation during many of the early daytime observations. This time of day should have corresponded with the lowest levels of DO based on traditional diurnal patterns (Wetzel 1975). Generally, this supersaturation will occur in the late afternoon. Further, if sufficient algal activity

exists to produce highly supersaturated water, the same activity will usually deplete the DO at night and in the early morning due to respiration. Additional data were obtained from an ongoing separate data collection effort by Tennessee Technological University for the Nashville District.* The unusually high saturation levels during early morning observations were also recorded during this effort. As this phenomenon is not consistent with historical algal processes observed at other sites, the CE-QUAL-W2 model will not, in its present form, reproduce such saturation levels at these times even when adequate inflow data are available for algal modeling. Therefore, the modeling of algae was not conducted.

55. DO adjustment was concluded with the DOM decay term set at 0.09 mg/ℓ per day. The best agreement between the observed and predicted profiles was achieved with this decay term and the rate multiplier coefficient function shown in Figure 5. The rate multiplier in the model adjusts the decay term as the temperature changes. For this application, the rate multiplier coefficient increased from 0.1 at 5° C to 0.98 at 25° C. The multiplier term remained constant at 0.98 for temperatures greater than 25° C. The maximum DOM decay term (0.09 mg/ℓ per day in this case) was multiplied by the rate multiplier to determine the decay rate for each cell at each time-step. The update interval (which is an input to the model) determines the frequency with

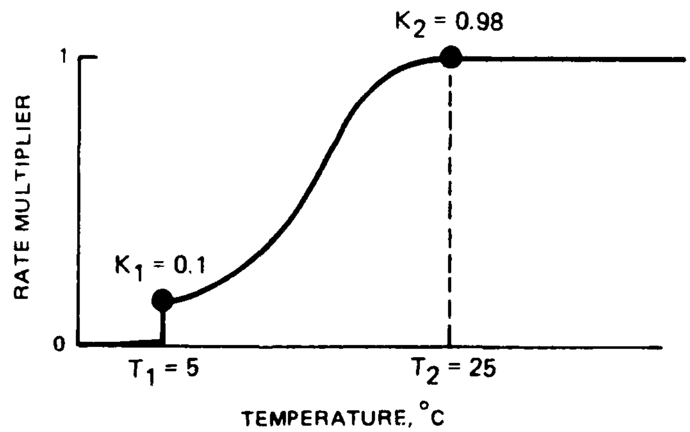

Figure 5. Rate multiplier

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* R. T. Brown. 1986. Unpublished data, Tennessee Technological University, Cookeville, TN.

which the rate multiplier is adjusted and can conserve computational time if chosen properly.

56. The DO verification results are given in Plates 7-12. The results were generally good. However, the supersaturation in the epilimnion shown in May, June, August, and September (Plate 12) could not be simulated with the existing data. The errors between the predicted and observed DO concentration at the surface sometimes exceeded 3 mg/ℓ. During periods when the pool was not supersaturated, the predictions were good, often within 1 mg/ℓ for the entire profile. The errors seen in Plate 7 for the July and September profiles were probably caused by inflow DO errors in the model input. This station was located near the inflow point and should have matched very closely with the inflow concentrations.

Final Verification

57. To increase the confidence in the model verification, a model/prototype comparison was made using a separate data set without making any further modifications to model parameters. The year 1981 was selected for final verification of the model. The hydrology, meteorology, and other boundary input were developed for 1981 and the April-October period was simulated. The equilibrium temperature changes used in adjustment were also employed in the verification. A comparison of a limited amount of observed data with the model predictions is given in Plates 13-24. The comparison was very favorable. It originally appeared that the surface temperatures were being slightly underpredicted by the model. This was due, in part, to averaging within the top layer by the model. The observed data, in all cases, included a measurement immediately below the water surface which is not directly comparable to model output. Significant stratification was rare, but when it occurred, the calibrated model predicted it well. Although only limited observed data were available for 1981, the comparisons supported the equilibrium temperature adjustments resulting from the adjustment phase.

58. A trend in DO concentrations similar to that encountered during adjustment was observed in the verification phase. The model predicted the hypolimnetic DO values well. For most comparison dates, it predicted the epilimnetic and metalimnetic regions well, but results for the dates on which supersaturated levels of DO occurred, such as 15 July, were not matched due to

the constraints (both in the input and the algorithm) on the type of DO modeling being performed.

59. Release water quality data had been collected during 1981. A comparison of the model-produced release qualities with the observed values was performed. The predicted and observed release temperatures are given in Figure 6 and the predicted and observed release DO concentrations are shown in Figure 7. The tailwater data were collected hourly by the United States Geological Survey (USGS) with Corps of Engineers funding. The model predictions of temperature and DO were reasonably close to the observed values. In the spring and summer, the release temperature observations were warmer than the predictions, and in the fall, the opposite was true. Any significant contact with the atmosphere between the time the water was released and the time it was sampled would, at least in part, have explained the errors. The standard error between the predicted and observed temperatures was 2.61° C. Much of the error stemmed from the spring discrepancies. Since the tailwater data collection location was about 400 m downstream of the dam on the right bank, atmospheric influence and mixing with previously released water could have had a noticeable impact on the releases prior to measurement.

60. The predicted versus observed release DO concentrations were acceptably close with a standard error of 0.87 mg/ℓ. The only period which produced a poor comparison was the month of May. The outflow for the first 15 days of May for 1981 averaged about 850 cu m/sec. This was an extremely low flow event for this project as the 1979 average for the same period was about 5,000 cu m/sec. The excessive error in DO during this period indicated that perhaps the decay coefficient chosen during adjustment was not accurate for all flow conditions. It appeared to provide reasonably good results for the majority of conditions, but not for very high retention times associated with low flows through this project. These conditions were not seen during the adjustment phase.

61. The results of the final verification indicated that the coefficients selected during adjustment were generally appropriate. The very limited quantity of comparison data, however, was a hindrance in accurately estimating the model's reliability. However, general trends indicated that extended modeling during very low flow periods may necessitate the reevaluation of the DOM decay coefficients. The errors between the predicted and observed release quality may have stemmed from incompatibility of the two data

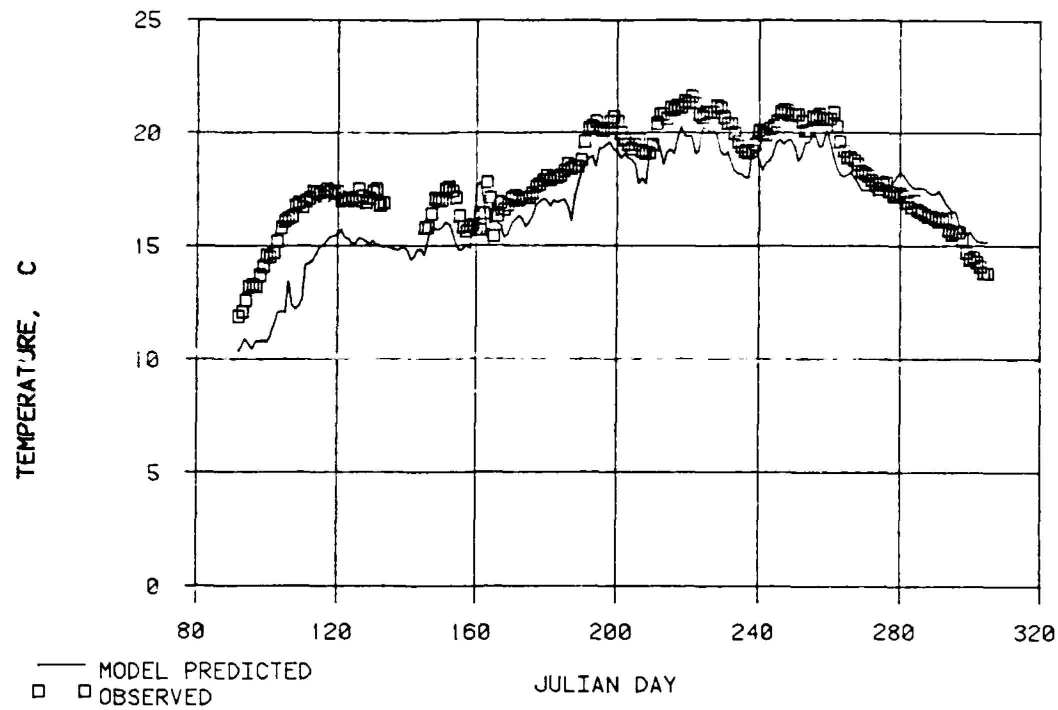

Figure 6. Predicted versus observed release temperatures

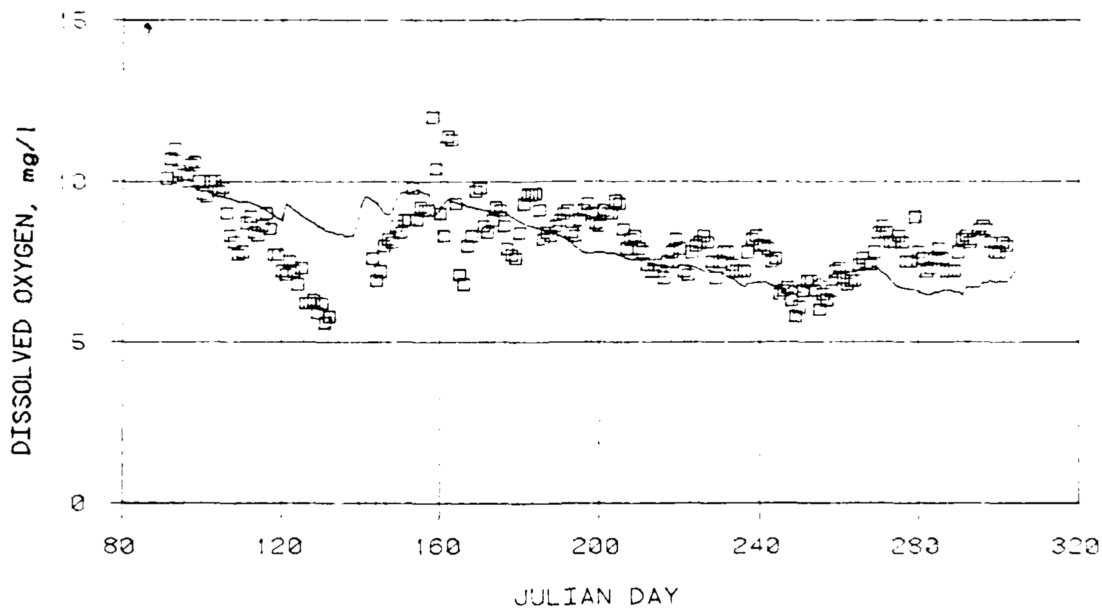

Figure 7. Predicted versus observed release DO concentrations

sets. The observed data were obtained by evenly weighting all 24 hourly observations, which produced daily averages of the release qualities. In this process, the data collected during zero-flow periods (nongeneration) were given equal weighting with those data collected during generation periods. The predicted release quality data were produced by model simulations using averaged daily release quantities evenly divided over the 24-hour period. These facts made model assessment based on this comparison very difficult. This comparison of release qualities could further have been compromised by any downstream circulation or mixing between the immediate releases and any previously released water in the tailrace area.

PART V: SIMULATION OF WET, AVERAGE, AND DRY YEARS

62. Simulations of the April-October period for a wet (1979), an average (1981), and a dry (1975) year, each designated by the Nashville District, were performed to evaluate the interactions between hydrology, meteorology, and stratification within the reservoir. The boundary conditions used for each of these simulations can be found in Appendix A.

63. The wet year, 1979, was simulated during the adjustment portion of the model study. Stratification during this year was present, but was usually weak due to the consistently high flows. Extensive warming of the water was rare as retention times were low. Sample velocity vector and temperature and DO contour plots are shown in Plates 25-34. Temperature contours are plotted across the longitudinal segments, which were shown in Figure 2. As mentioned in paragraph 21, the segments were 1.61 km for branch 1 and 8.05 km for branch 2. Longitudinal stratification can be seen during the periods of weak vertical stratification, such as Julian day 302, which is the end of October. Moderately strong stratification occurred in late June, as is shown by the temperature contours for Julian day 180. Very little DO stratification was observed at any time during 1979. The DO stratification that existed was generally along the longitudinal axis and was caused by gradual decay and changes in the inflow DO.

64. This year, 1979, exhibited the largest flow contribution from the tributaries for the 3 years simulated. The impact of these contributions appeared to be small. The tributary peaks tended to coincide with the high flow periods and were overshadowed.

65. The average year, 1981, was simulated during the verification phase of the study. The early spring of this year was dry as seen in Table 1. However, June was wet and the summer and fall were average. Velocity vectors and constituent contours are provided in Plates 35-44. This year provided a good opportunity for the evaluation of the relationship between meteorology, hydrology, and stratification. In June 1981, the inflow and outflow from the model were consistently high for a period of several days. It seemed that this system, which is prone to unstable stratification, should have been destratified during this period of high flows. However, in the model results, stratification existed during this high flow period, was destroyed, and then redeveloped. Control over the stratification appeared to lie with the

Table 1

Average Monthly Discharge from Cordell Hull Reservoir

Month	Average Monthly Discharge, cu m/sec, for Year 1975	1979	1981
April	13,184	8,875	1,368
May	5,751	3,738	2,274
June	2,575	3,149	6,602
July	1,185	3,191	2,981
August	834	3,805	2,863
September	1,099	4,861	2,716
October	2,235	4,059	2,559

equilibrium temperature. A drop in equilibrium temperature during this period resulted in almost total destratification by vertical mixing. When the equilibrium temperature rose again, the stratification returned.

66. Reservoir destratification may be tied to storm events. When a storm passed, the equilibrium temperature dropped significantly and the wind speed usually increased, which helped mix the upper layers. The cooling of the water surface and the wind and internal mixing combined to quickly disperse vertical stratification. Longitudinal stratification was evident even during periods when vertical stratification was not.

67. The dry year, 1975, was then simulated. Flows during the late spring were extremely high, but the summer flows were extremely low (see Table 1). The low summer flows, due largely to the spring drawdown of Lake Cumberland upstream for repair work on Wolf Creek Dam, resulted in long retention times and much higher DO decay. The lower flows also produced higher inflow temperatures for the Cumberland River at Celina than for the wetter years. These higher temperatures became the hypolimnetic temperatures within the Cordell Hull Reservoir. The inflow temperatures, although higher for this year than for the other years simulated, were still not high enough to cause an interflow or an overflow. The in-reservoir water was consistently warmer than the inflow for the simulation period. The constant full-reservoir-depth withdrawal through the hydropower intakes prevented significant cool-water or warm-water resource conservation. Therefore, the strength of the stratification, based on temperature differential, for this year was not increased over the wetter years. These trends are evident in the velocity vector and contour plots in Plates 45-54.

68. Generally, for all 3 years simulated, the velocity fields were unchanging except during extreme flow events. The direction and relative length of each velocity vector remained mostly constant for various discharges. For most situations, the differences between velocity fields could have been approximated by scaling of the entire field based on total discharge. For example, if the flow through the reservoir were doubled, the velocity vectors would, in general, retain their basic direction and double in length (magnitude). Only during very low discharges did a flow reversal occur, and then the velocities were very small. The hydrodynamic dominance prevented the formation of density currents having the same order of magnitude as the advective currents. The density influences were present but were not easily noticeable in the velocity fields due to the generally high flow through this system.

69. Discharge appeared to control the strength of the stratification but did not dictate its existence for the range of flows examined in this study. Equilibrium temperature was the key to the creation and destruction of stratification. The process resulting in temporary destratification was the same as that observed in the fall when many lakes destratify. The surface waters were cooled and began to sink. Mixing ensued and this process continued downward through the water column. Wind mixing aided in the breakup of stratification, but its effects could not be separated from the other components in the mixing process. The high velocities in the lake probably also assisted in the breakup of stratification by helping transport water vertically.

70. For each of the three years simulated, slight to moderate stratification existed, periodically, from April until late October. A short-lived upward surge in equilibrium temperature in October was shown to quickly produce significant stratification in the system although it had been almost completely devoid of thermal stratification just a few days earlier.

PART VI: SUBMERGED WEIR EVALUATION

71. The adjusted and verified model was then used to preview the potential impacts of placing submerged weirs at the mouths of two embayments in the reservoir. At about RM 332 on the Cumberland River near Granville, Tennessee, the embayments of Martin and Dillard creeks enter the main stem of Cordell Hull Reservoir. A Corps of Engineers recreational site has been developed in this area which includes much of the two embayments. Use of this recreational site for fishing and water-contact recreation has been limited due to the cool water temperatures. One proposed solution to the problem is the installation of submerged weirs at the mouths of the embayments which surround the recreational area. This solution would have the potential to warm the embayments by reducing the intrusion of the colder bottom flows from the main stem. This warming effect would encourage contact recreation such as swimming and skiing and would provide an environment perhaps more suitable for a warmwater fishery.

72. To evaluate the installation of these weirs, some changes in the main-stem model were necessary. To simulate the embayments properly, the bathymetry in this area had to be refined. The branch morphology had been "roughed in" for the main-stem modeling by treating these embayments as one branch each, when they actually consisted of two major arms each. The Martin Creek embayment consists of Martin Creek and Dry Fork. The Dillard Creek embayment consists primarily of Dillard Creek and Little Indian Creek. Each of these four creeks was declared a branch in the weir evaluation portion of the study. The bathymetry in the branches was derived, by hand, from 1.52-m-interval contour maps. The discretization of these branches was the same, vertically, as the two main branches. The segment length was set the same (400 m) as in the main-stem representation of these embayments.

73. No gaged flows, observed temperatures, or DO concentrations were available for any of the four creeks. Drainage areas were employed as before to determine the inflow quantities. The temperatures and DO concentrations of the inflows were assumed to be the same as the tributary values provided by the Nashville District in the main-stem modeling. The USGS in Nashville was consulted concerning drainage areas.* Martin Creek was the only one of the

* Personal Communication, 14 Jul 1986, from Jerry Lowery, US Geological Survey, Nashville, TN.

four with a known drainage area. The individual inflows for all four creeks were determined from the contour maps by tracing the ridge lines, determining the drainage areas, and applying a drainage area ratio to gaged flow on the Roaring River. The resulting drainage areas and branch identification follow:

Branch No.	Creek Name	Drainage Area, sq km
3	Martin Creek	96.0
4	Dry Fork	25.9
5	Dillard Creek	11.6
6	Little Indian Creek	44.0

74. The discretization and geometry of branches 1 and 2, which comprise the main stem, remained the same as in the previous work. Defeated Creek, a branch in the main-stem simulation, was declared a tributary to conserve computational time for the weir evaluation since it should not have affected the results in the area of interest.

75. Weir simulation is not a standard option in the model. Therefore, a technique similar to that used by Gordon (1981) was employed to simulate weirs. The velocities and longitudinal momentum terms were set to zero at the location of the artificial weirs. An alternative to this method would have been alteration of the bathymetry to reflect a one-segment bump in the reservoir bottom at the desired location. However, a disadvantage of the latter technique was that the weir would have had a crest width equal to the segment length in the branch containing the weir. In this case, the weir crest would have been 400 m across. This was considered unacceptable and the former alternative was employed.

76. The location and height of the weirs were established. In defining the branches, the downstream limits of Martin and Dillard Creek embayments were established at the Highway 53 bridge which crosses both embayments close to the main stem of the reservoir. The simulated weirs were also located at these bridge crossings for both embayments as shown in Figure 8. The weir crest elevations were established at 151.4 m.* This elevation was chosen to correspond to the interface elevation between two model layers and to allow

* Personal Communication, 16 Sep 1986, from Mr. J. K. Brown, US Army Engineer District, Nashville, Nashville, TN.

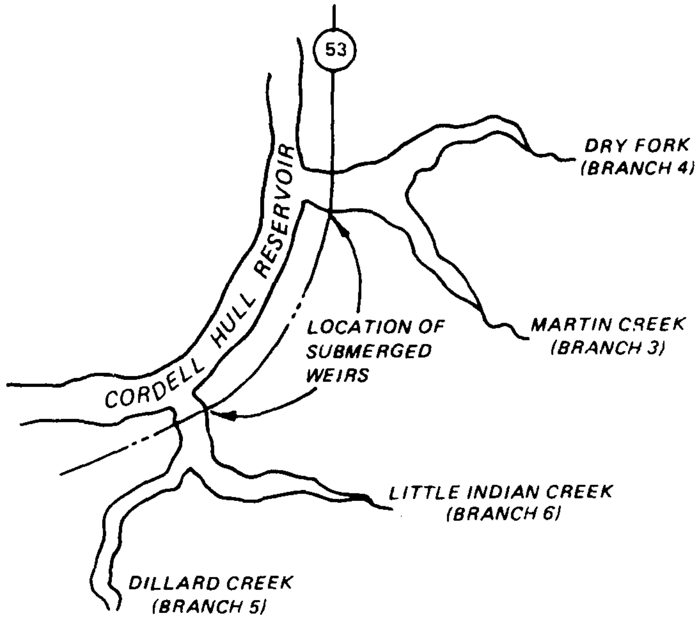

Figure 8. Location map for submerged weir analysis

ample freeboard for boating traffic in and out of the embayments, even during low water periods.

77. The year 1975 was chosen to be used in the weir evaluation because of the long period of extremely low inflows during the summer as seen in Table 1. Since a potential problem foreseen with the proposal was DO degradation in the embayments, the use of 1975 data should have revealed the worst resulting conditions of the 3 years. Simulations were performed both with and without the weirs in place. Sample results are shown in Plates 55-57.

78. The net exchange rate of water between the main stem and the embayments was not noticeably impacted by the installation of the weirs. This was reasonable since the flow exchange with the main stem was controlled by water-surface differential, which was not appreciably affected by the presence of the weirs. The lower level intrusion was, however, effectively stopped by the weirs. In the simulations without weirs in place, the density-driven cooler water pushed into the embayments and the surface waters moved from the embayment into the main stem to maintain continuity. Therefore, without weirs, the embayment water quality closely followed that in the main stem. However, with weirs in place, some impact on embayment water quality was induced.

79. In general, the weirs produced very little of the desired impacts. The desired warming effect was not displayed in the results. The surface

layers were warmed slightly, but not appreciably. The lower and middepth layers were actually made cooler by the weir placement. The cool water from the homogeneous temperature condition in April was somewhat trapped by the weirs. The water behind the weirs was slowly warmed by surface heat influx and diffusion with very little help from hydrodynamic mixing. Meanwhile, the lower layers of water in the main stem were being quickly withdrawn and replaced by warmer inflows. Therefore, a temperature gradient did develop across the weirs, but with the cooler water on the embayment side instead of the anticipated main-stem side. Without weirs, density currents and hydrodynamic mixing quickly conformed the embayment quality to that of the main stem.

80. The stagnation of this water behind the weirs produced an anticipated, undesirable result. The DO behind the weirs was unchanged at the surface after weir installation, but the lower layers experienced substantial decay. The upper layers were free to exchange with the water surface and the main stem, which prevented serious decay problems. However, the lower layers were essentially motionless and gradually reached unacceptably low levels of DO as stratification prevented atmospheric exchange and oxygen demands on the water persisted. The DOM decay coefficients established during adjustment of the model (Figure 5) were also employed during the weir evaluation.

81. One beneficial aspect of the weir placement was the stability of the stratification. If ample DO could be maintained behind the weirs, a stable environment for fishery development might be created by placement of weirs. This would require further evaluation of the stratification under higher inflow and tributary flow conditions to ensure that no hydrodynamically induced flushing of the embayments occurred.

PART VII: HYDROPOWER OPERATION ANALYSIS

82. After the weir evaluation was completed, a short-term data-intensive modeling effort was undertaken using the adjusted main-stem version of CE-QUAL-W2 to evaluate the short-term impacts of hydropower operations, meteorology, and hydrology on the reservoir characteristics. The data, which were supplied on a daily basis for the main-stem modeling, were provided at hourly intervals for this simulation. This amount of data would have been impractical for seasonal evaluations such as the main-stem effort described in Part V. The Nashville District selected a 2-week period beginning on 29 July and ending on 11 August 1981 for the intensive simulations. The model was not altered from the main-stem version with the exception of input data.

83. Figure A1 shows the discharge through the hydropower facility over the 2-week period (Julian days 210 through 223). Inflow corrections which were used in earlier work were not employed here due to the short time span involved. Contour and vector plots from this simulation are shown in Plates 58-62. As expected, the temperature contours near the outlet were drawn downward developing a warmwater "wedge" in two dimensions. When hydropower was not operating, the buoyancy effects of the wedge forced it toward purely vertical stratification. The resulting vertical velocities were evident in the vector plots.

84. An underflow was observed during the simulation. This demonstrated the influence of stratification on hydrodynamics during higher flow periods, an influence which was not as easily discernable by examination of the velocity vector output. This underflow moved along the bottom until it completely diffused.

85. The diurnal variations in water quality were more thoroughly evaluated by producing temperature and DO contour and velocity vector output every 3 hr for a short period. The day 81214 (2 August 1981) was chosen as a representative day for evaluation. Plots for this day are shown in Plates 63-70. These plots provided insight into the surface heat exchange process as well as the system's response to starting and stopping of the hydropower units. On this day, the hydropower units were started between 10 a.m. and 11 a.m. with a total discharge of about 2,125 cu m/sec. The discharge was increased at about 1 p.m. to approximately 4,500 cu m/sec and remained there until the units were turned off at about 9 p.m. This was a fairly typical

operation during this period. Surface cooling due to a nighttime drop in the air temperature, and thus the equilibrium temperature, was evidenced in the results by the deepening of the contours at the water surface caused by vertical mixing. The actual velocity vectors associated with this surface mixing were masked by the other velocities in the field. Stronger stratification in the surface layers was evident during the daytime hours when heat influx was high. No significant diel variations in DO occurred, so contour plots of this constituent are not shown in this section.

86. Outflow from the structure substantially influenced the velocity field within the reservoir. The no-discharge velocity field was dominated by density-driven currents as buoyancy effects tried to equilibrate the stratification. The velocity field under hydropower operation conditions was much different with a very dominant unidirectional longitudinal flow pattern throughout the reservoir.

87. Even though the impact on the velocity field was great, the short-term effects of hydropower operation on the reservoir stratification were minimal except near the dam. The warmwater wedge development and breakup impacted the stratification only in the first few miles upstream of the structure. The DO levels also showed very little response to the operation of the hydroturbines. Therefore, starting and stopping of hydropower did not appear to significantly impact the overall reservoir stratification. More substantial impacts on the reservoir stratification appeared to be induced by daily heat influx and nightly heat efflux.

PART VIII: CONCLUSIONS

88. The application of CE-QUAL-W2 to Cordell Hull Reservoir, Tennessee, provided several insights into the character of the lake. The model verification process showed that, with proper adjustment, the model can adequately predict the temperature and DO regimes in this reservoir. These results also indicated that CE-QUAL-W2 was an appropriate choice of model for this reservoir.

89. The causes behind the dynamic nature of the thermal stratification patterns in the reservoir may be postulated from the tests. The equilibrium temperature appeared to be a dominant parameter in the development and breakup of stratification. The flow rate through the reservoir was also important in that the travel time affected the amount of warming which could occur, thereby determining the strength of stratification. An evaluation of the stratification patterns during a period of consistently high flow indicated that stratification could exist at high discharges. During this period, a drop in the equilibrium temperature quickly diminished the strength of the stratification and, in a short time, virtually destroyed it. The time required to build or destroy stratification was found to be small. Often, significant temperature stratification was developed or destroyed within a very few days based on simulation of daily averaged data.

90. The highly advective character of the system meant that the longitudinal velocities were generally much larger than the vertical velocities. The hydrodynamic patterns within the reservoir rarely changed significantly. Flow reversals were very uncommon and were observed only during very low flow periods. The impacts of stratification on the velocity field were present, but limited. The differences between the velocity fields for equal flow but different stratification conditions were almost undetectable.

91. The results of the study indicated that the verified model provides a useful tool for comparative analyses. However, due to the limited amount of observed water quality data for verification, and the nature of the model adjustments (equilibrium temperature in particular) to achieve the verification, use of the predictions in an absolute manner may not be wise when accuracy is important. Before the results may be used without reservation, a further evaluation of the microclimate at the reservoir and the DO in the reservoir is recommended.

92. Since equilibrium temperature proved to be very important in the development and breakup of stratification, and the computed equilibrium temperatures from the Nashville Airport weather station were adjusted for use at the reservoir, the development of a relationship between the microclimate at Cordell Hull Reservoir and that at Nashville is suggested for any future model application to this reservoir. A short-term data collection effort on the reservoir similar in format to that of Troxler and Thackston (1977) would probably suffice. An effort of this type should include the collection of wind speed and direction, air temperature, dew point temperature, cloud cover, and barometric pressure.

93. In an application to DeGray Lake, Arkansas, Martin (1987) observed a strong relationship between the wind speed and the heat exchange due to evaporative heat loss as would be expected from the empirical equations of heat transfer. The equilibrium temperature approach to heat transfer does not separate the evaporative heat exchange from the other components. Even though a similarly strong correlation between the evaporative heat loss and wind speed should exist at Cordell Hull Reservoir, this could not be adjusted for the significantly lower wind speeds at Cordell Hull Reservoir compared to those at Nashville. Such adjustment would require recomputation of the equilibrium temperatures and coefficients of surface heat exchange for the reservoir; however, this was not possible for lack of available data.

94. A separate modeling concern was the reliability of the DO results. The adjustment/verification results were good even though DO supersaturation levels were not modeled. The 1979 and 1981 years exhibited only minor DO decay as the water passed through the reservoir. Therefore, the DO concentrations were relatively insensitive to the model coefficients which were adjusted to represent this constituent. The only year of the three simulated which had significant DO decay was 1975, for which no comparative data existed.

95. As discussed previously, another concern was the unusually high DO saturation data observed at the lake during periods when the DO levels have traditionally been depleted. This supersaturation was not reproducible by CE-QUAL-W2 due to the number of constituents modeled and the sparsity of water quality data. This phenomenon should be analyzed with a short field study. An overnight evaluation of the DO profiles in the lake should reveal a depleted period from respiration if, in fact, algal photosynthesis is

generating the supersaturation. The unusual timing of the supersaturation would make the results of an evaluation of this sort interesting to a wide range of parties.

96. The weir analysis results indicated that little of the desired warming of the branches could be expected with the installation of submerged weirs at the mouths of the Martin and Dillard Creek embayments. The prevention of lower level exchange between the main stem and the embayments caused the hypolimnetic water behind the weirs to become stagnant. Subsequently, these DO concentrations became depleted. Further, the weir evaluation results from the 1975 simulation showed that DO concentrations may reach unacceptably low levels. The weirs provided only minor thermal increases and substantial DO degradation. However, they did provide a region with stable stratification, unlike the main stem.

97. A short-term hydropower evaluation was performed which demonstrated the effects of hydrodynamics on stratification for the period selected. The warmwater wedge resulting from the drawdown of the thermocline at the outlet was of particular interest. This wedge developed during generation periods and was buoyed up during periods of no discharge. The nighttime cooling of the surface waters was also evident. The cooler waters generated vertical diffusion and mixing of the upper layers.

98. In summary, the model evaluation of the Cordell Hull Reservoir provides insight into the relationship between the stratification, hydrodynamics, and meteorology of the system. The highly advective nature of this reservoir means that it is difficult to do anything within the reservoir to impact the in-reservoir or the release water quality. The in-reservoir quality is dictated almost wholly by the quality of the inflows. If selective withdrawal were usable here, perhaps some resource conservation could be effected: however, the high outflows are withdrawn from top to bottom, making the retention time low for the entire water column. This problem prevents the modification of the release quality unless the in-reservoir water quality is modified as the withdrawal patterns are essentially the same for all stratifications and flow rates. The only obvious changes which could significantly impact the water quality are a change in the inflow quality or the meteorology or a structural change to the project (e.g., weirs).

99. In general, without some physical change to the reservoir or a change in the weather, the only way to substantially change the in-reservoir

water quality (and thereby the release water quality) is to change the inflow water quality. Upstream changes to the operations of the Wolf Creek and/or Dale Hollow dams might influence the Cumberland River water quality at and below Cordell Hull Reservoir. As these two projects are storage impoundments, the problems posed by full-depth withdrawal and unidirectional flow of Cordell Hull may not be encountered.

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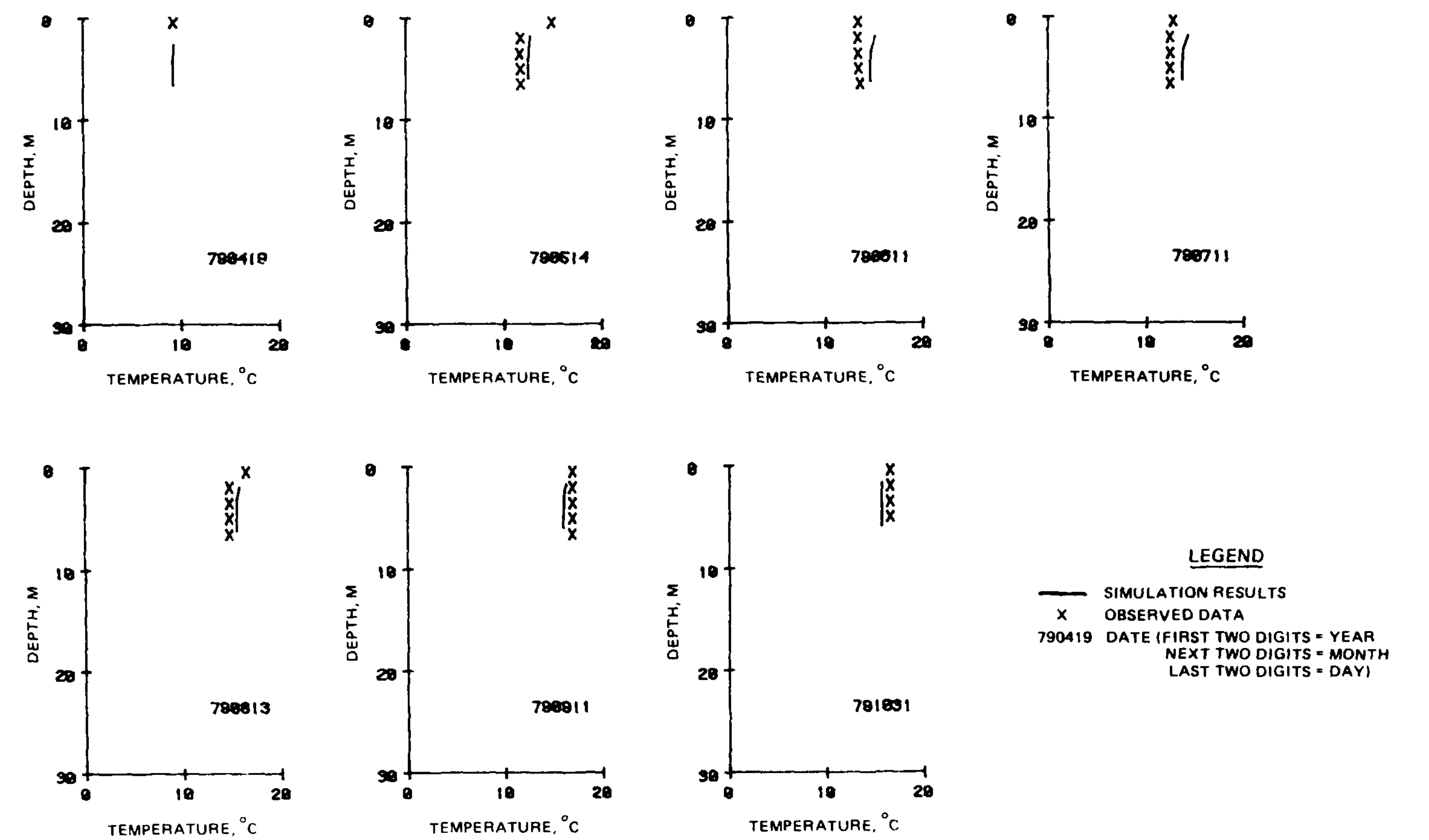
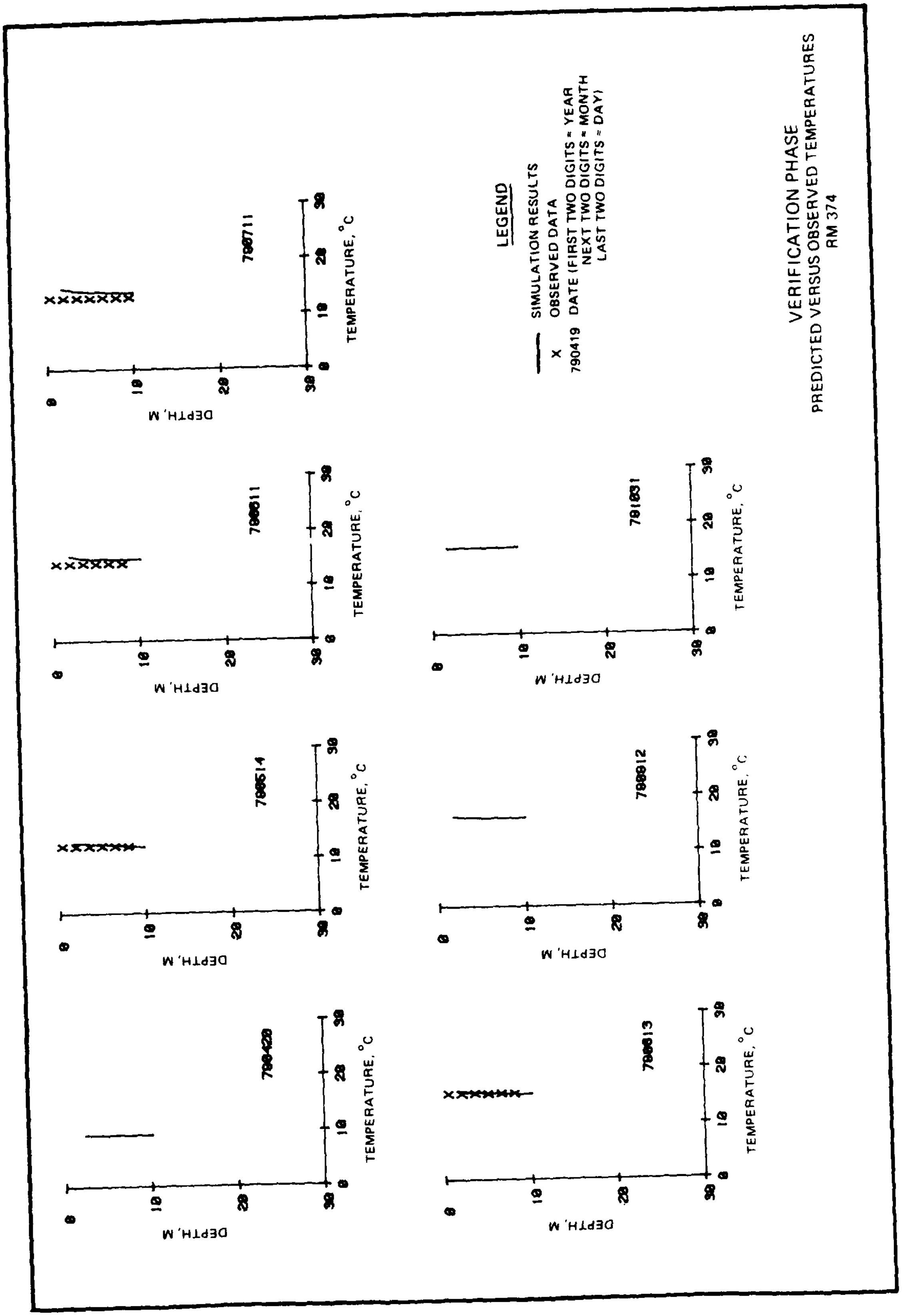


VERIFICATION PHASE
PREDICTED VERSUS OBSERVED TEMPERATURES
RM 380

PLATE 1


VERIFICATION PHASE
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RM 374
LEGEND
SIMULATION RESULTS
X OBSERVED DATA
790419 DATE (FIRST TWO DIGITS = YEAR
NEXT TWO DIGITS = MONTH
LAST TWO DIGITS = DAY)
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790514
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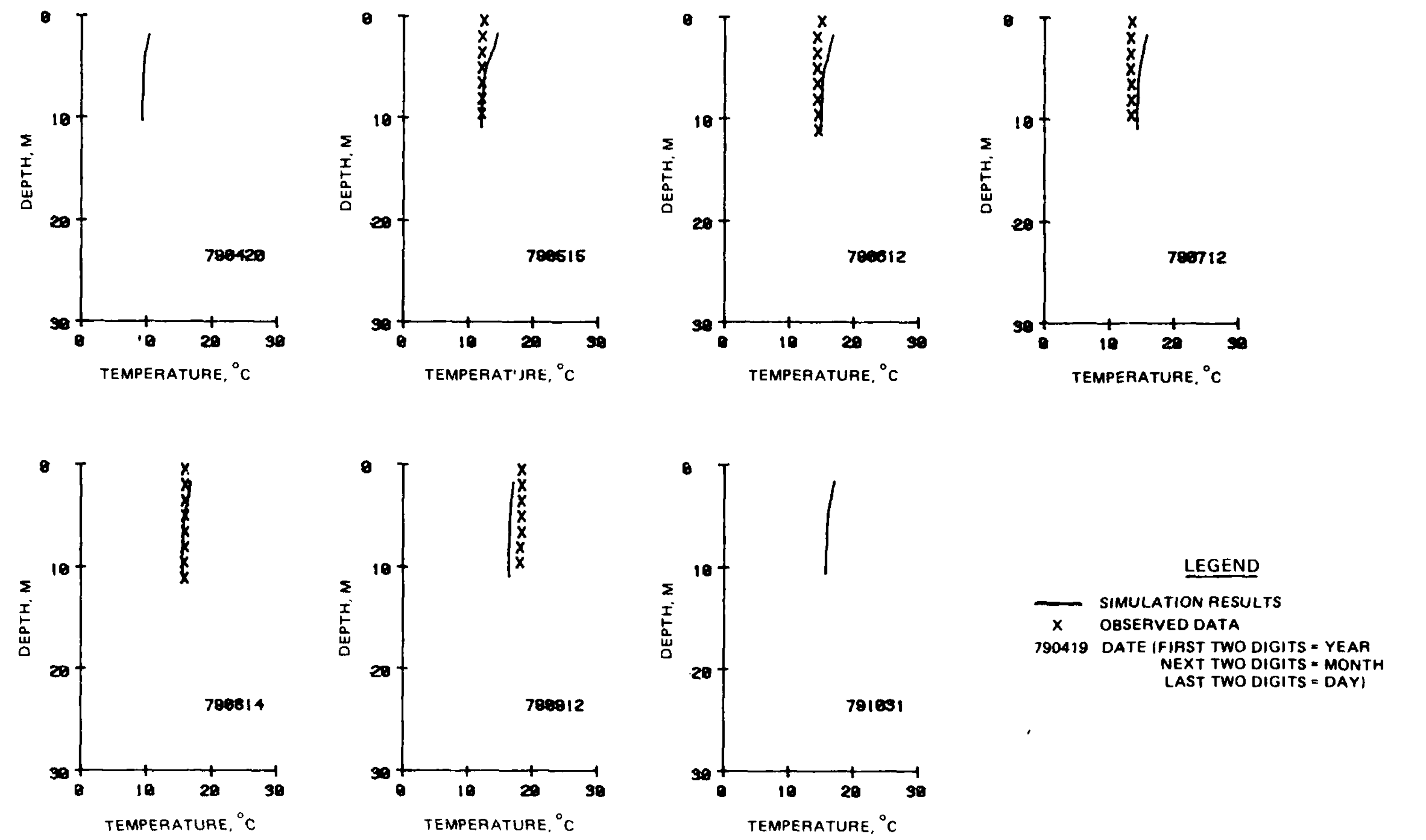
790813
790912
791031
DEPTH, M
TEMPERATURE, °C

PLATE 2



VERIFICATION PHASE
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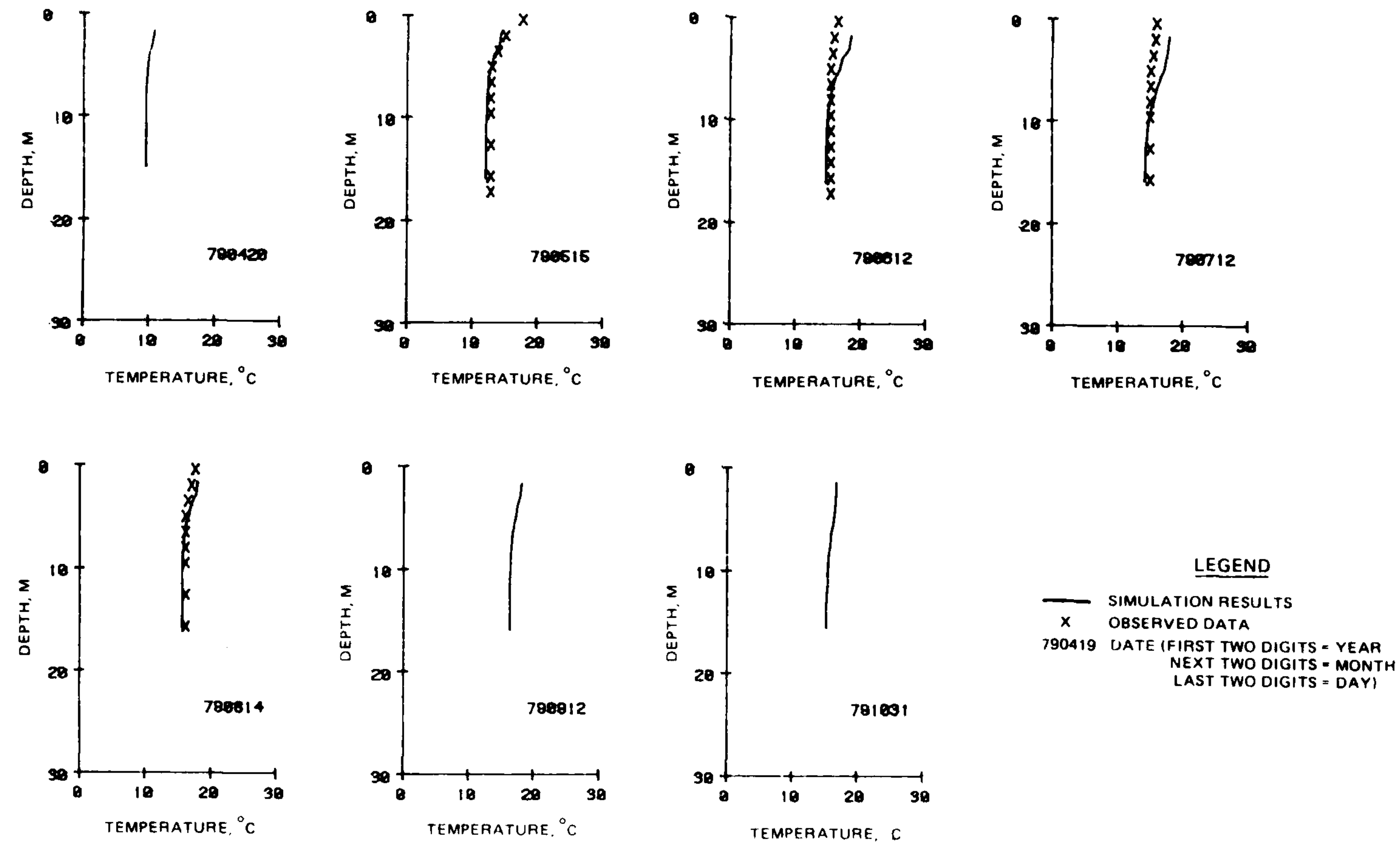
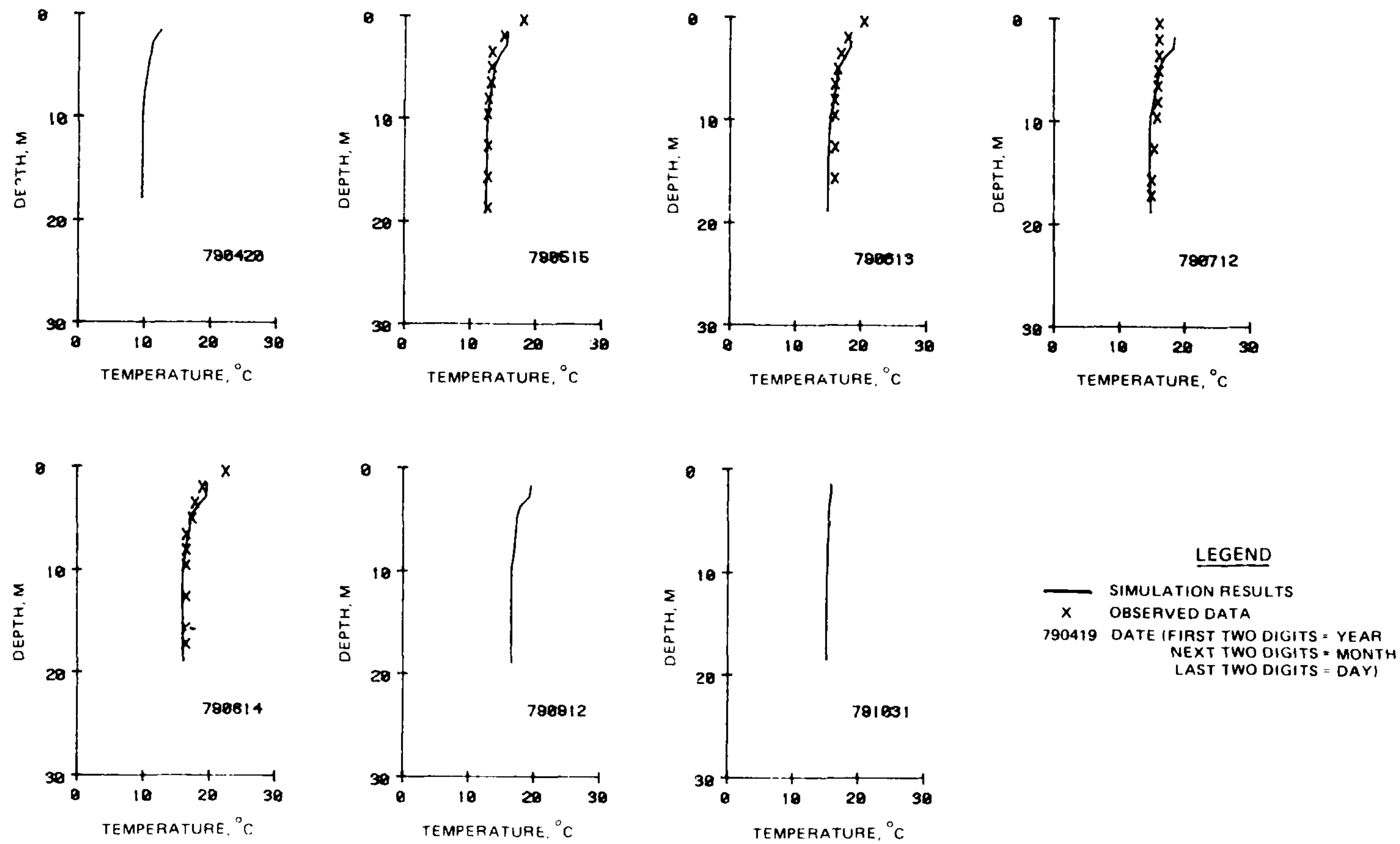
RM 358



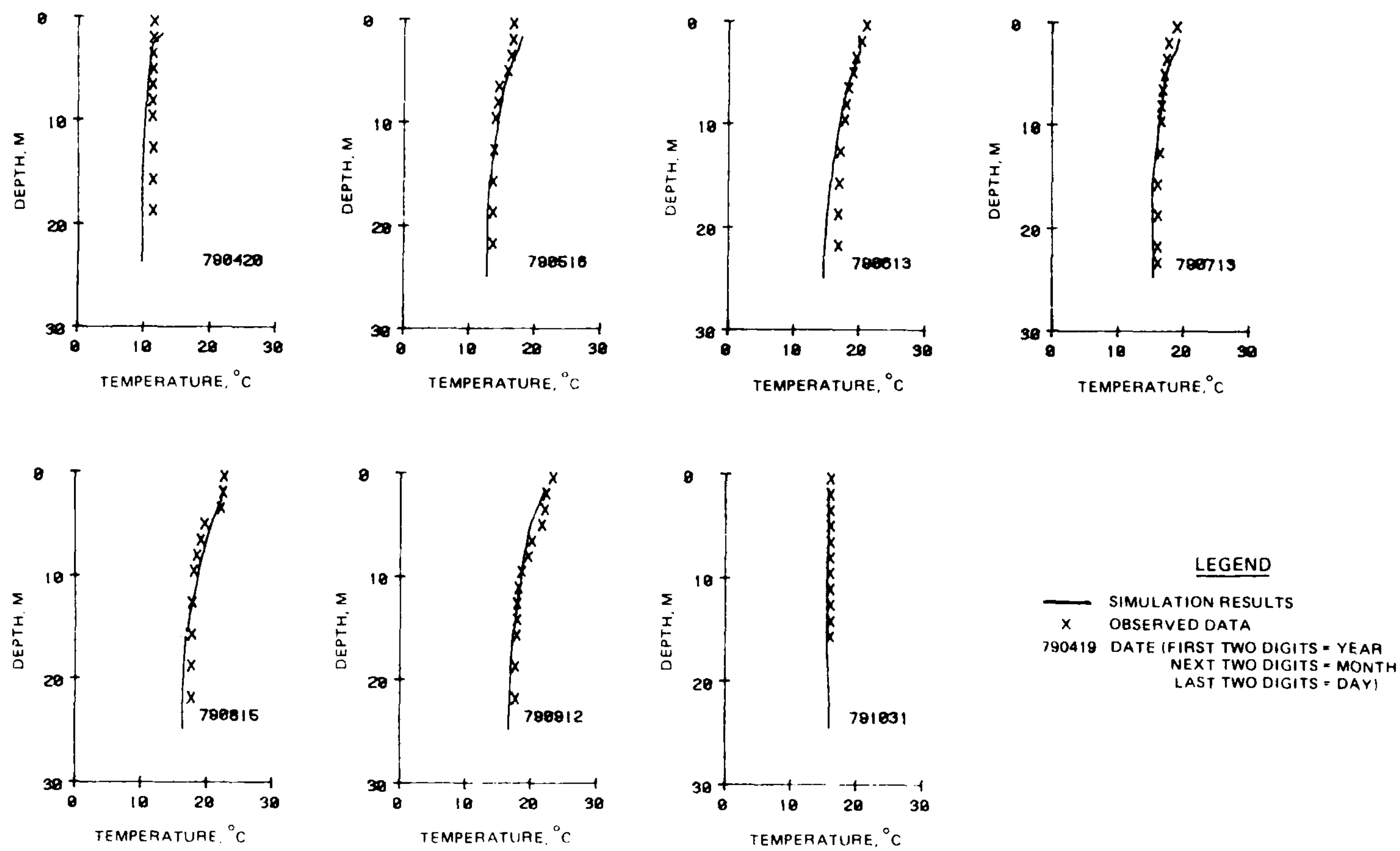
VERIFICATION PHASE
PREDICTED VERSUS OBSERVED TEMPERATURES
RM 341

PLATE 4



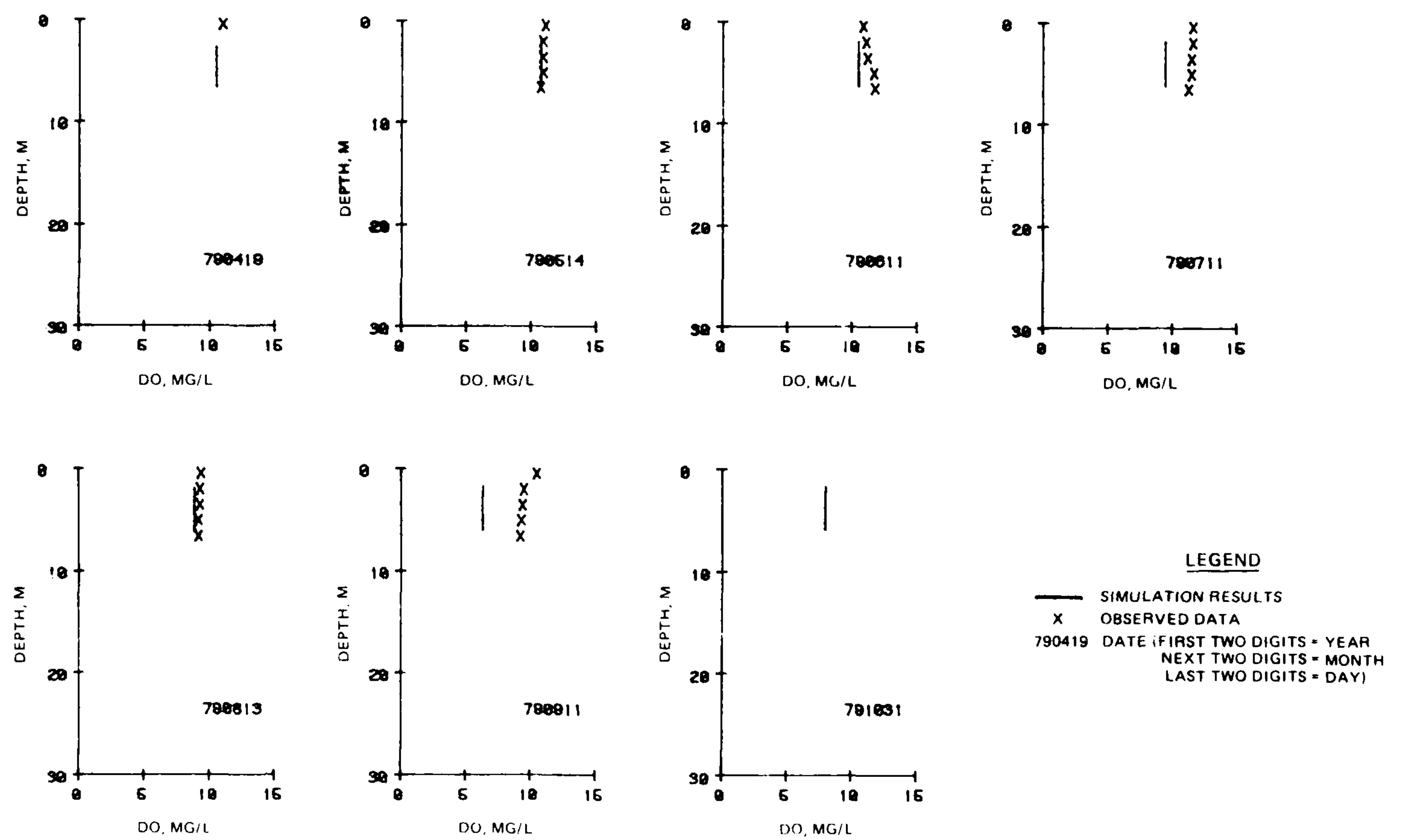
VERIFICATION PHASE
PREDICTED VERSUS OBSERVED TEMPERATURES
RM 328

PLATE 5



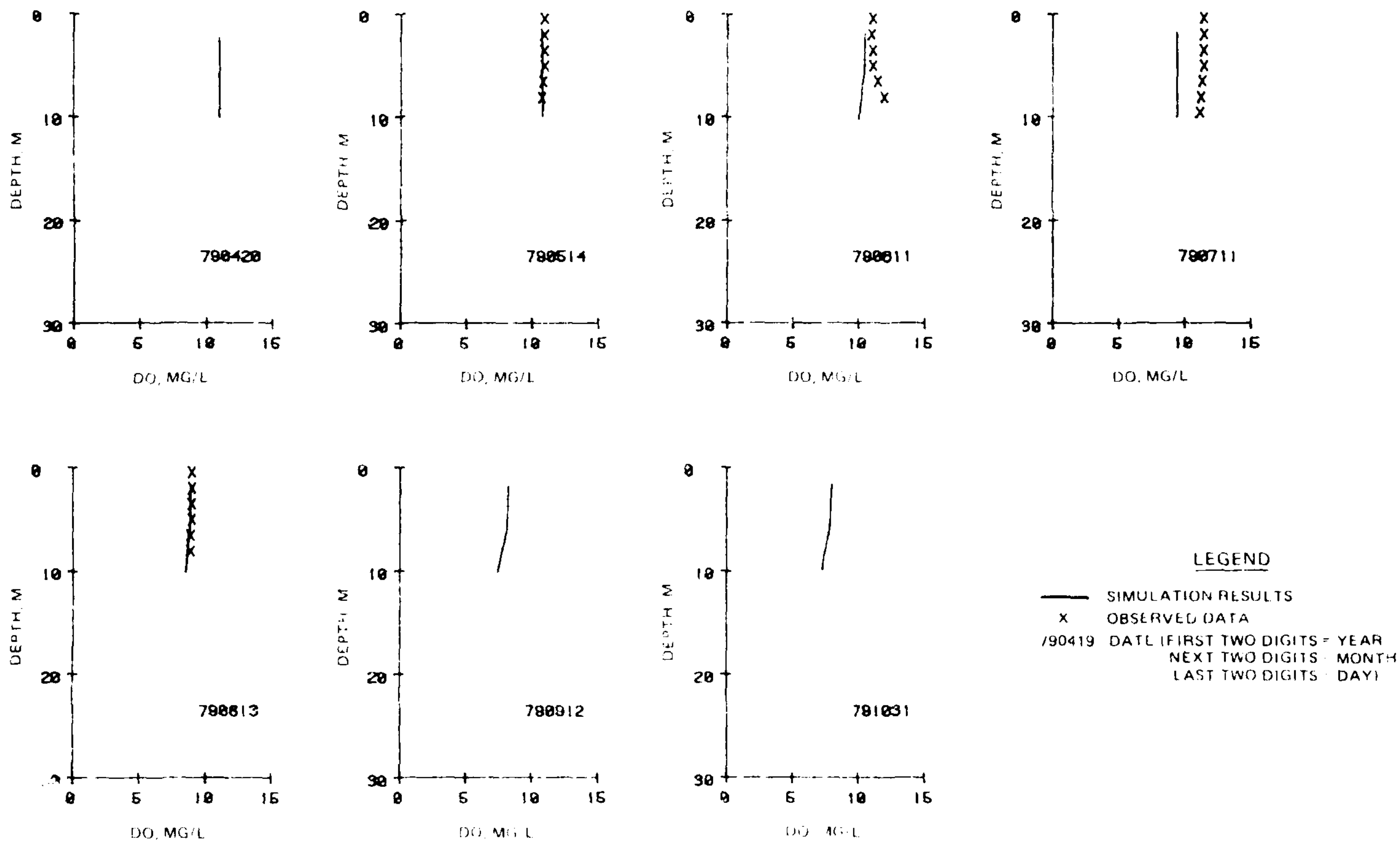
VERIFICATION PHASE
PREDICTED VERSUS OBSERVED TEMPERATURES
RM 314

PLATE 6



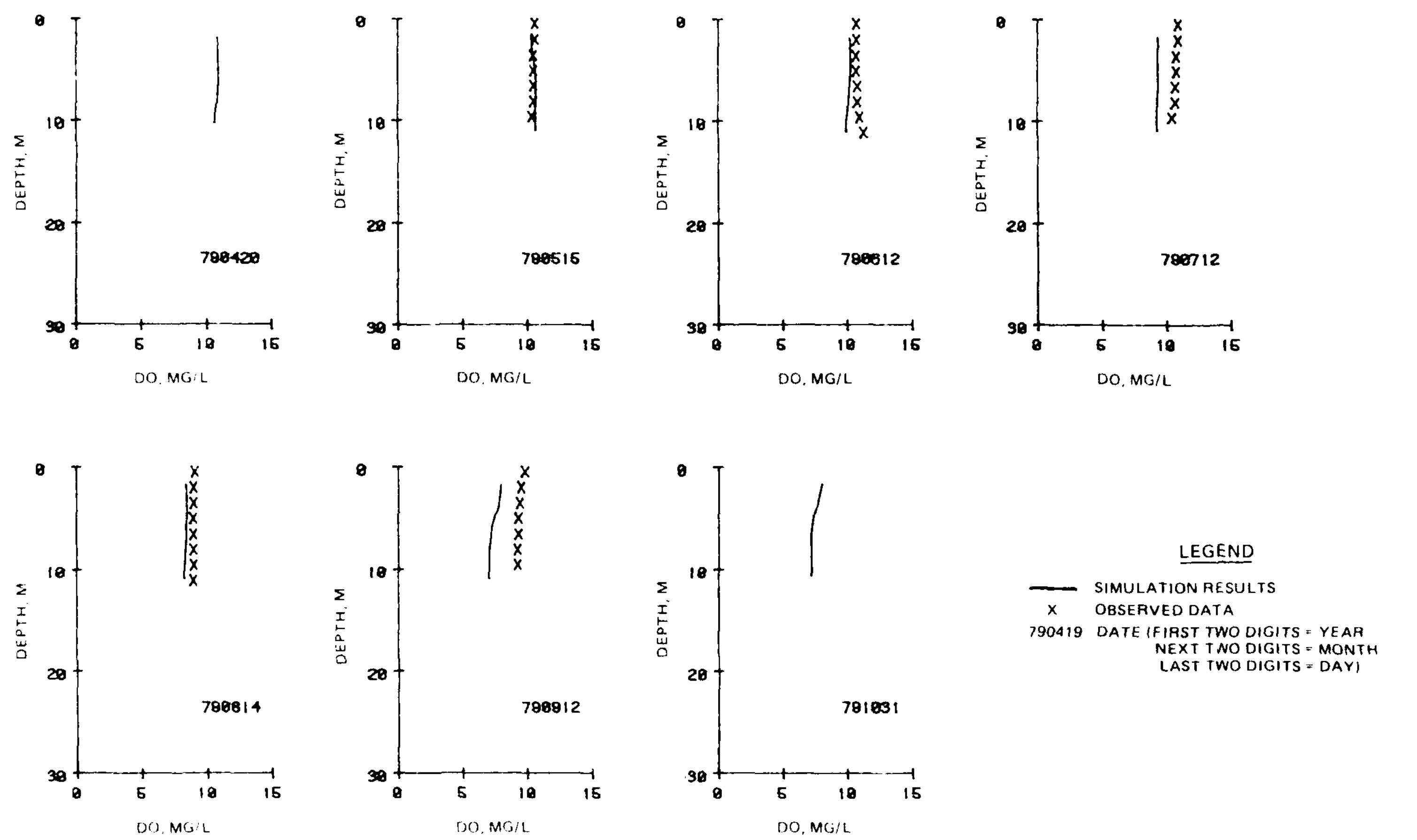
VERIFICATION PHASE
PREDICTED VERSUS OBSERVED DO
RM 380

PLATE 7



VERIFICATION PHASE
PREDICTED VERSUS OBSERVED DO
RM 374

PLATE 8



VERIFICATION PHASE
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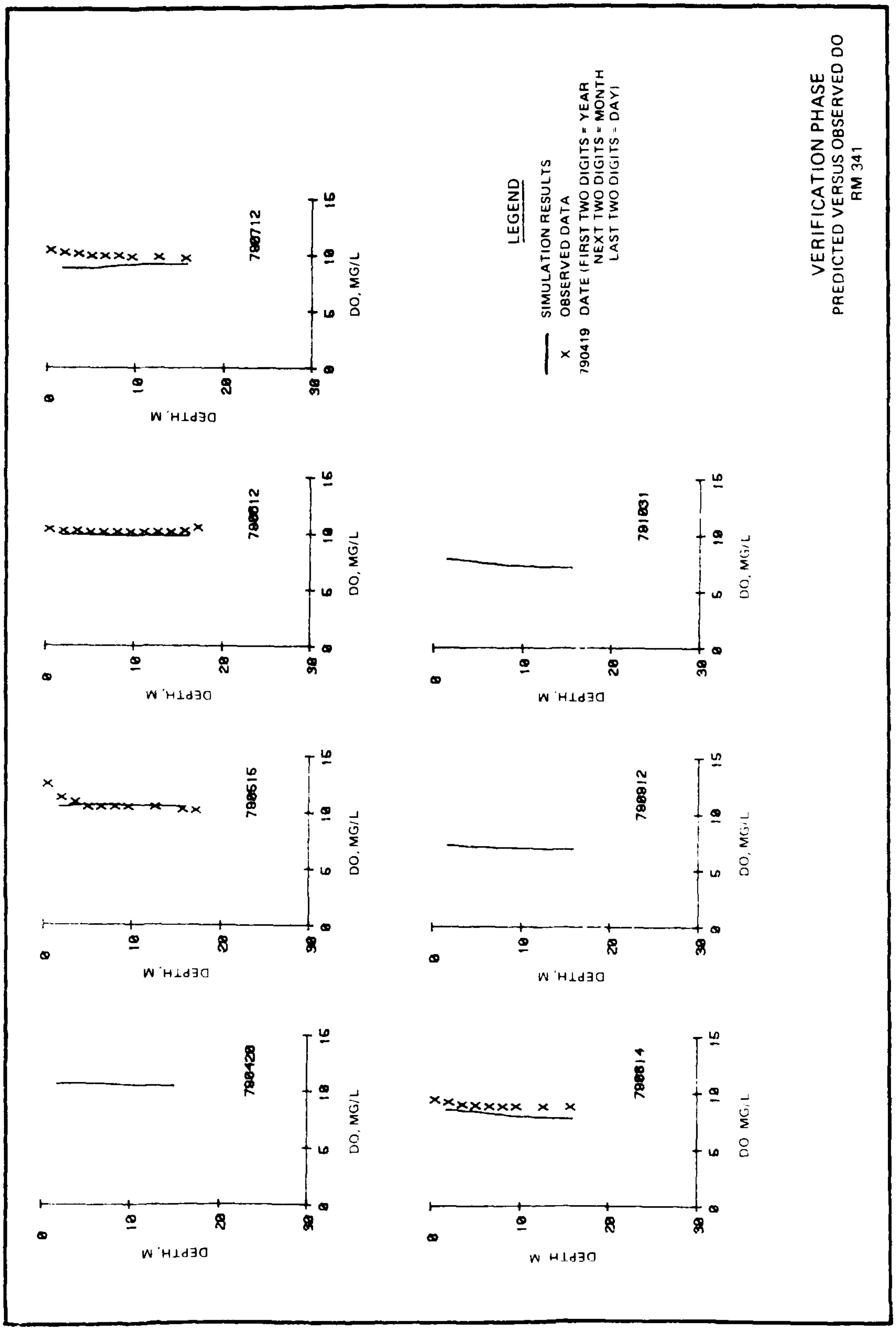
RM 358


VERIFICATION PHASE
PREDICTED VERSUS OBSERVED DO
RM 341
LEGEND
SIMULATION RESULTS
X OBSERVED DATA
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NEXT TWO DIGITS = MONTH
LAST TWO DIGITS = DAY)
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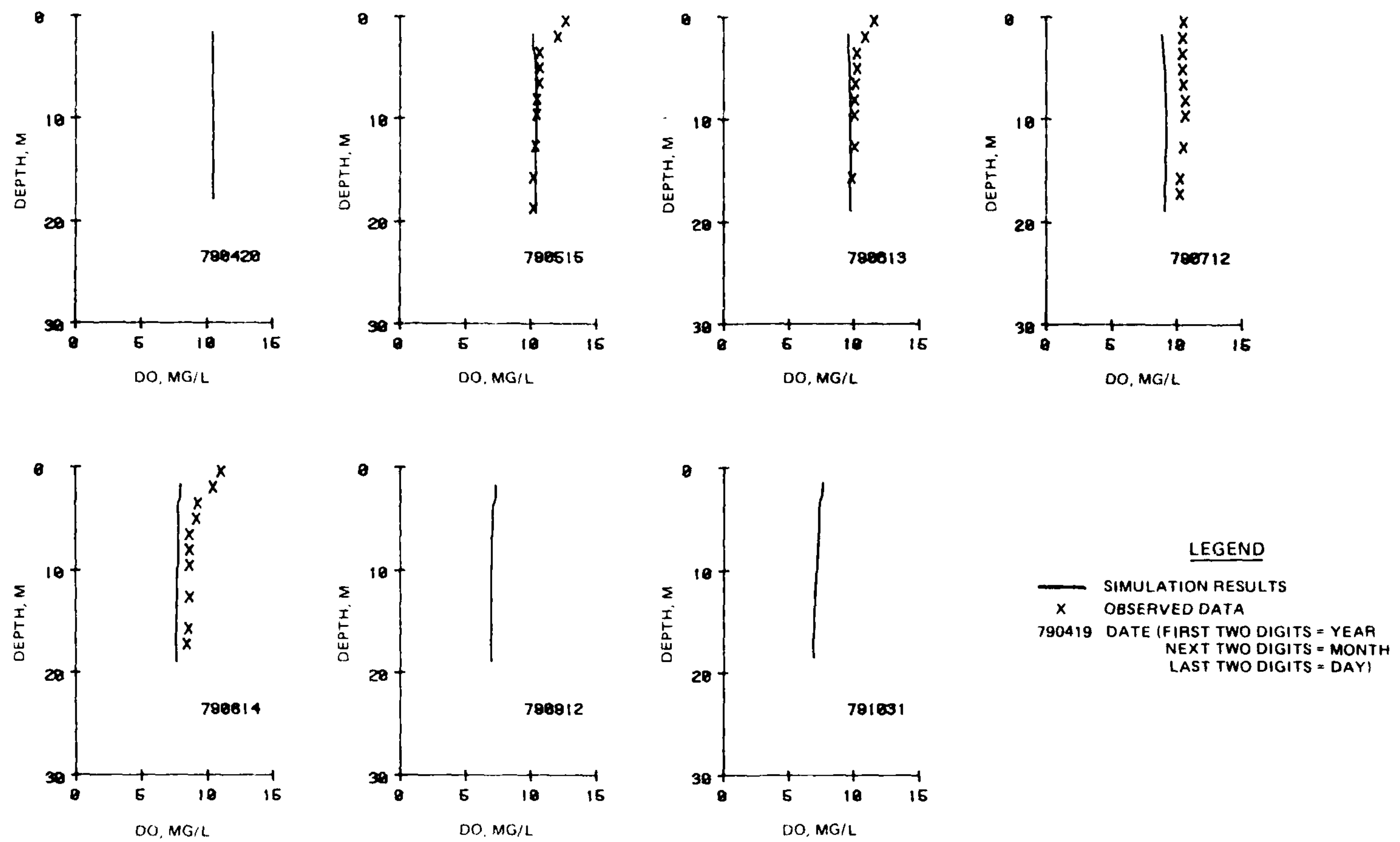
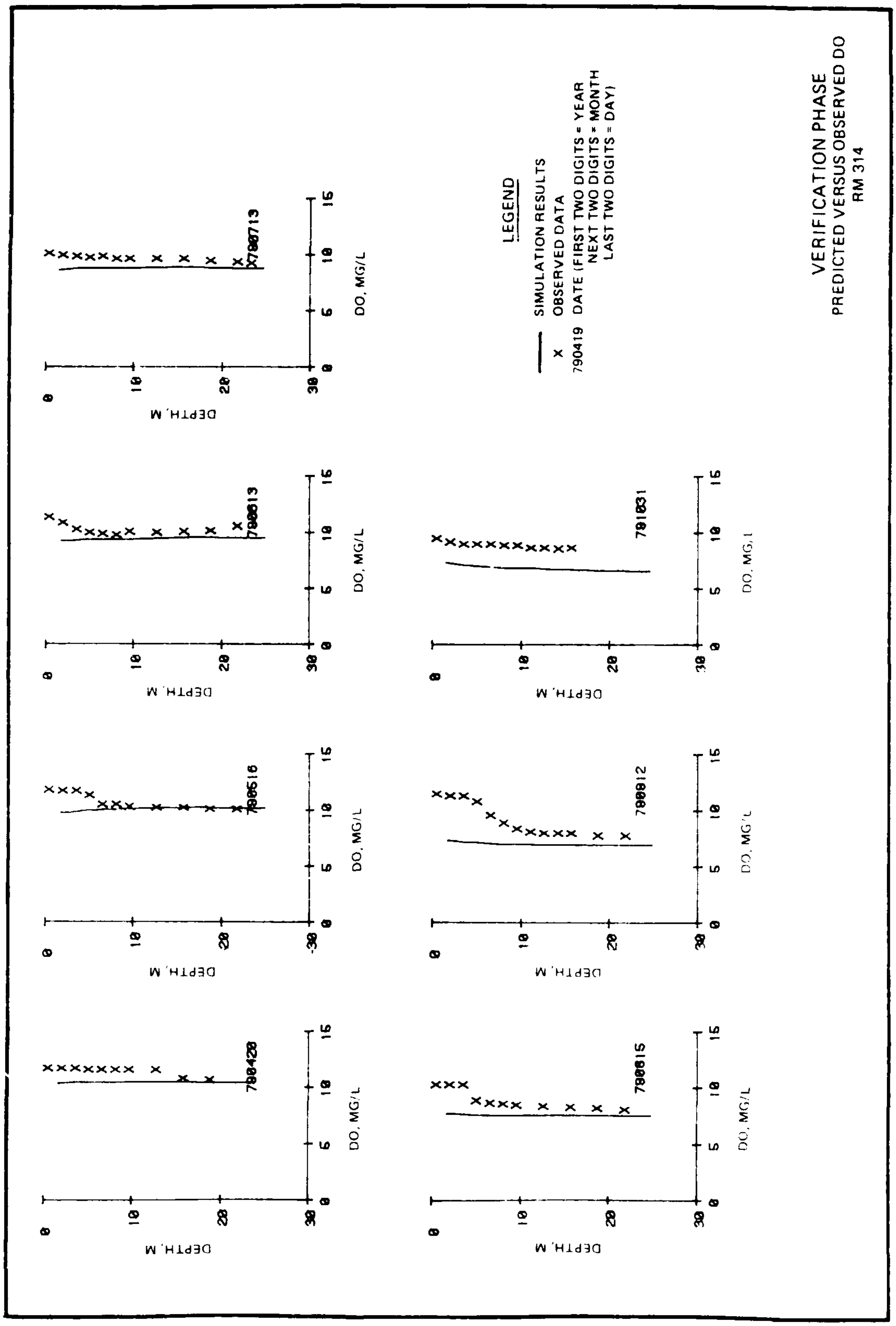
DEPTH, M
DO, MG/L

PLATE 10



VERIFICATION PHASE
PREDICTED VERSUS OBSERVED DO
RM 328



LEGEND
SIMULATION RESULTS
X OBSERVED DATA
790419 DATE (FIRST TWO DIGITS = YEAR
NEXT TWO DIGITS = MONTH
LAST TWO DIGITS = DAY)
VERIFICATION PHASE
PREDICTED VERSUS OBSERVED DO
RM 314
DEPTH, M
DO, MG/L
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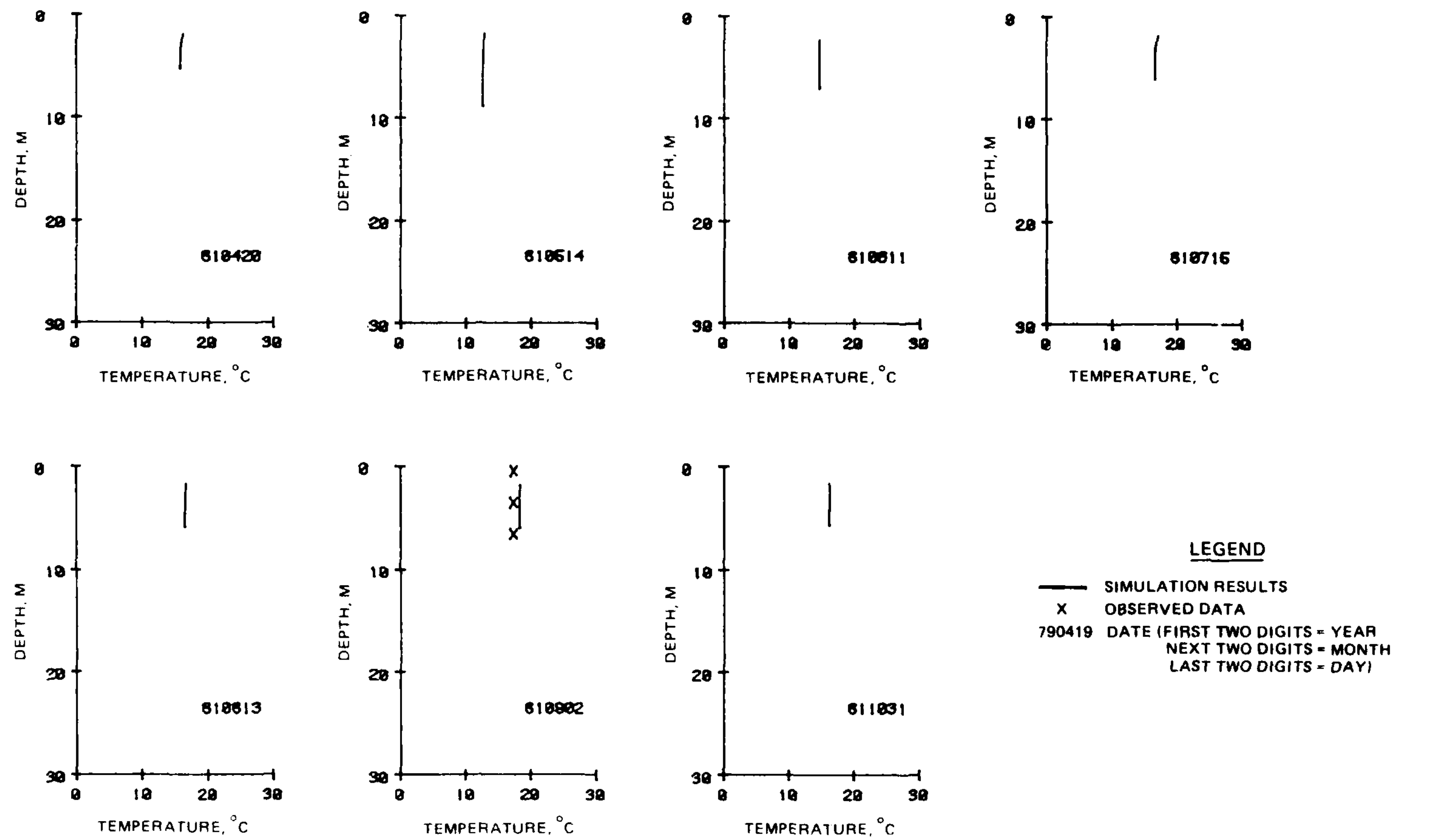
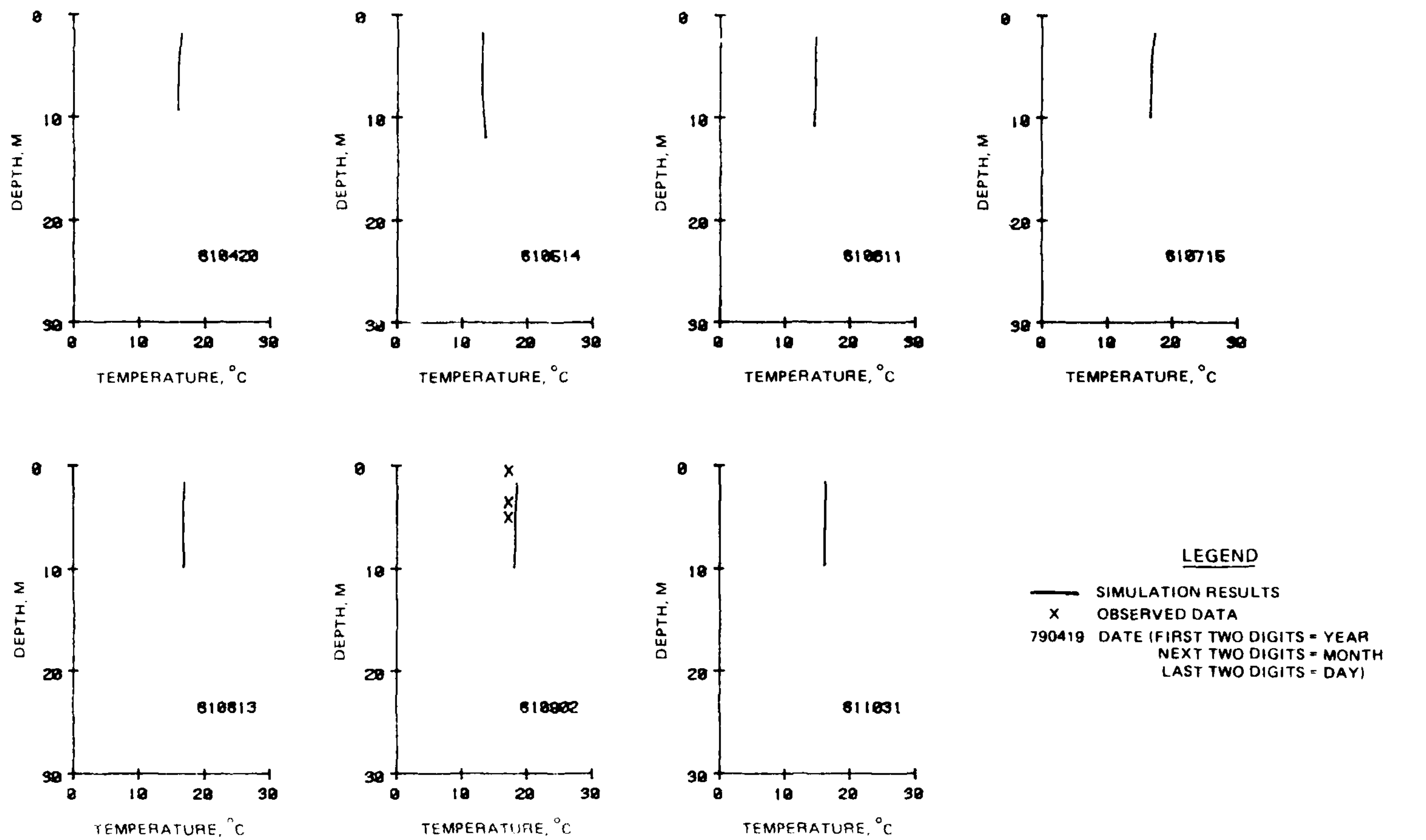
790912
791031

PLATE 12



FINAL VERIFICATION PHASE
PREDICTED VERSUS OBSERVED TEMPERATURES
RM 380

PLATE 13



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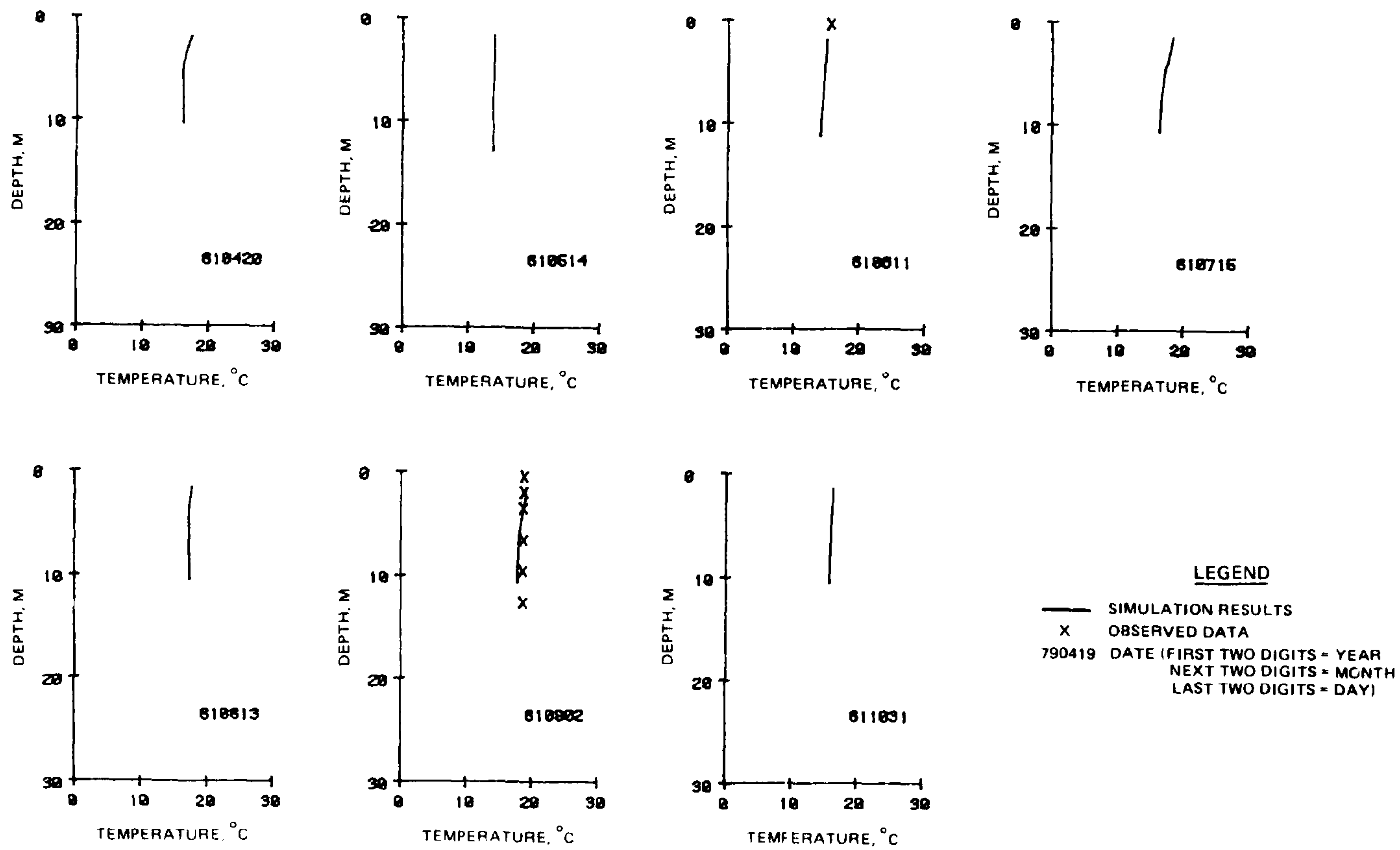
PREDICTED VERSUS OBSERVED TEMPERATURES
RM 374

PLATE 14



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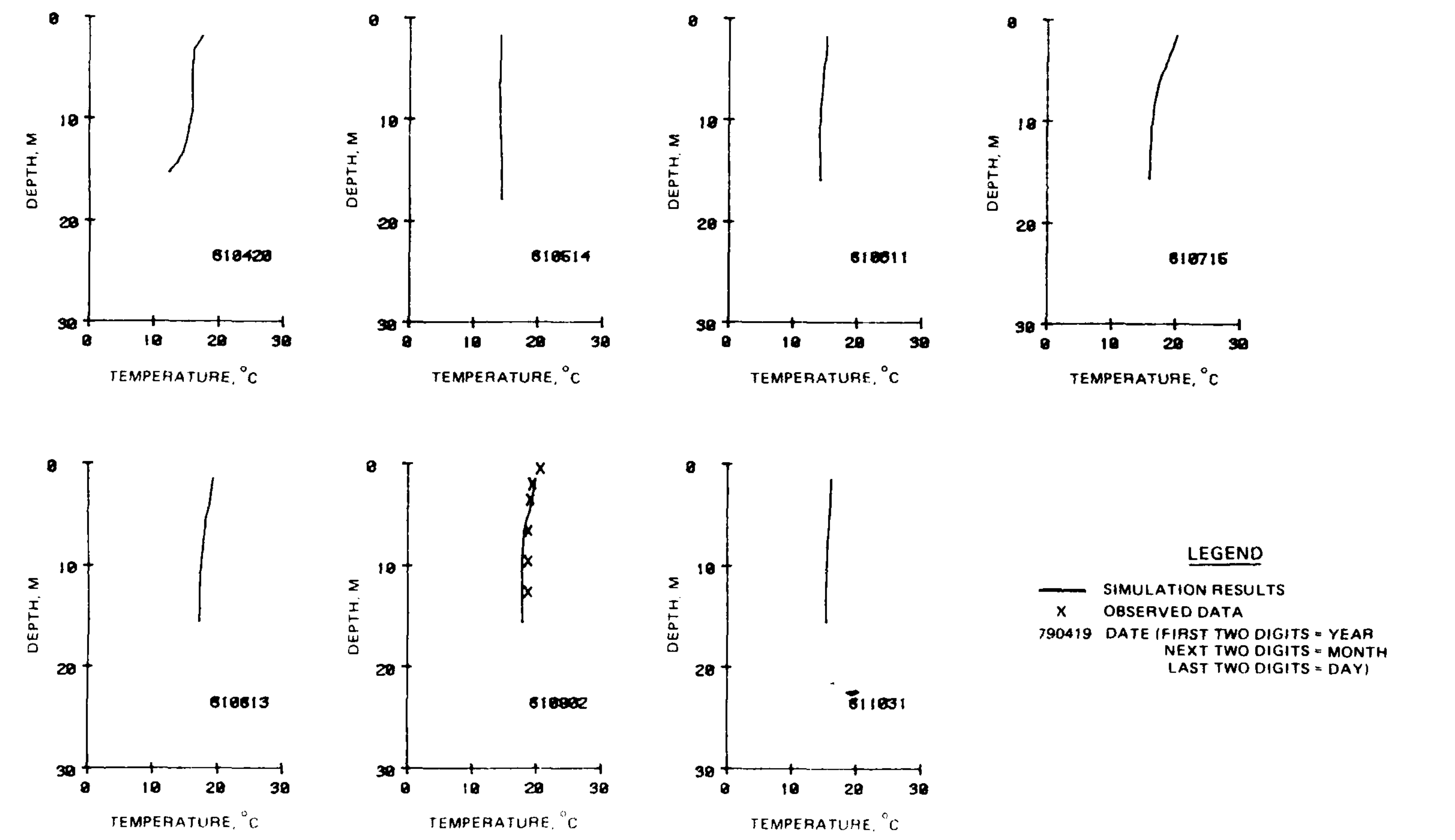
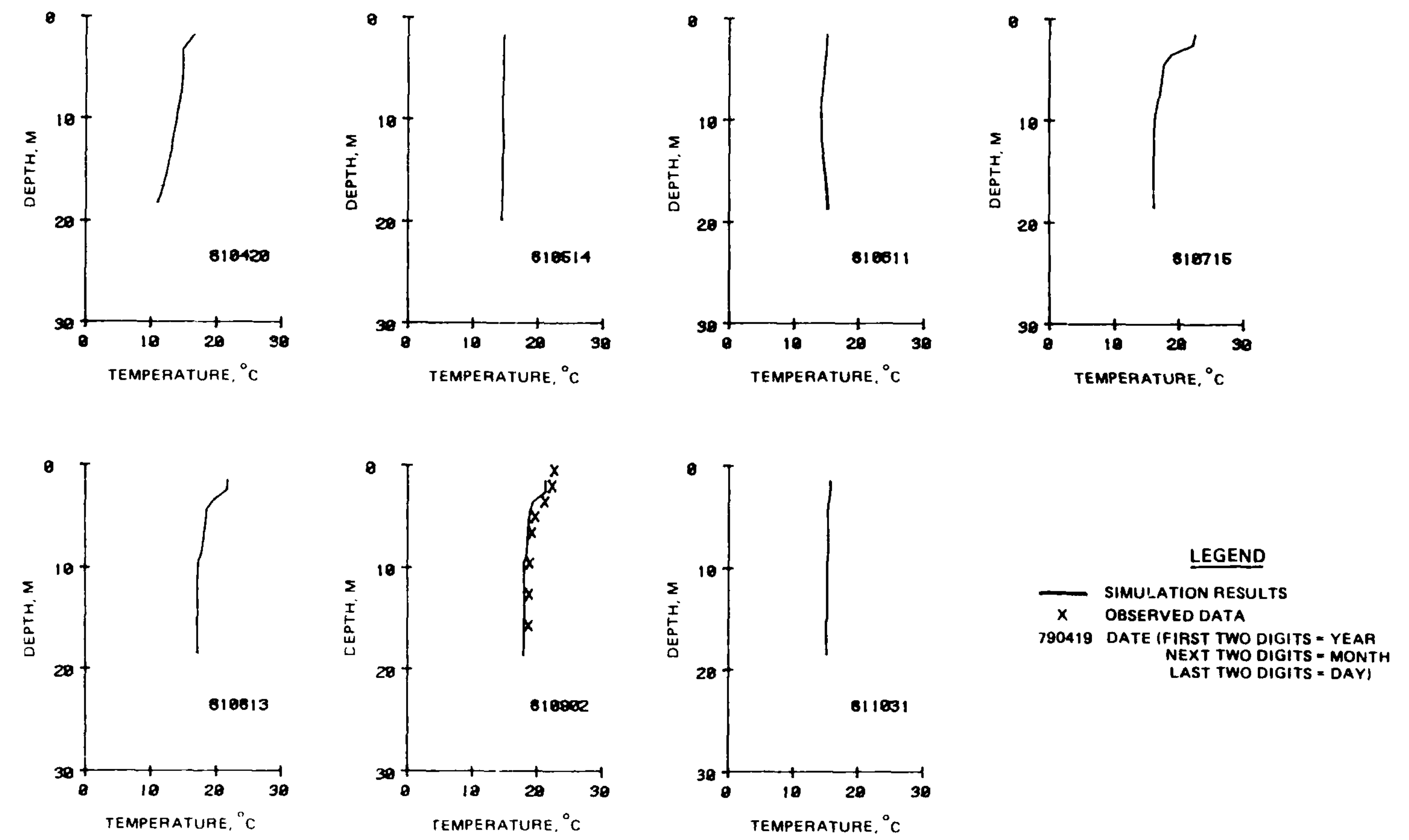
PREDICTED VERSUS OBSERVED TEMPERATURES
RM 358



FINAL VERIFICATION PHASE
PREDICTED VERSUS OBSERVED TEMPERATURES
RM 341

PLATE 16



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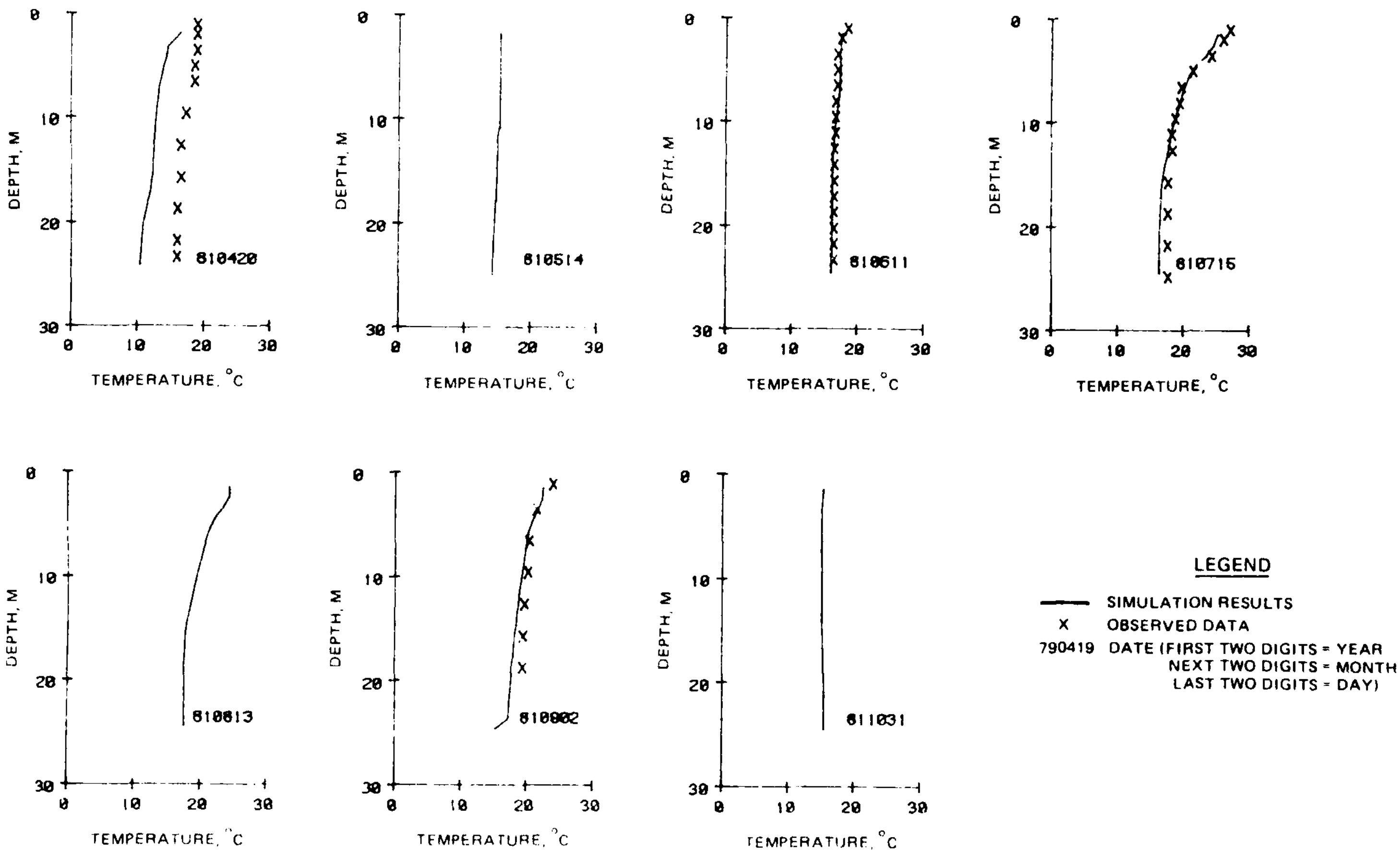
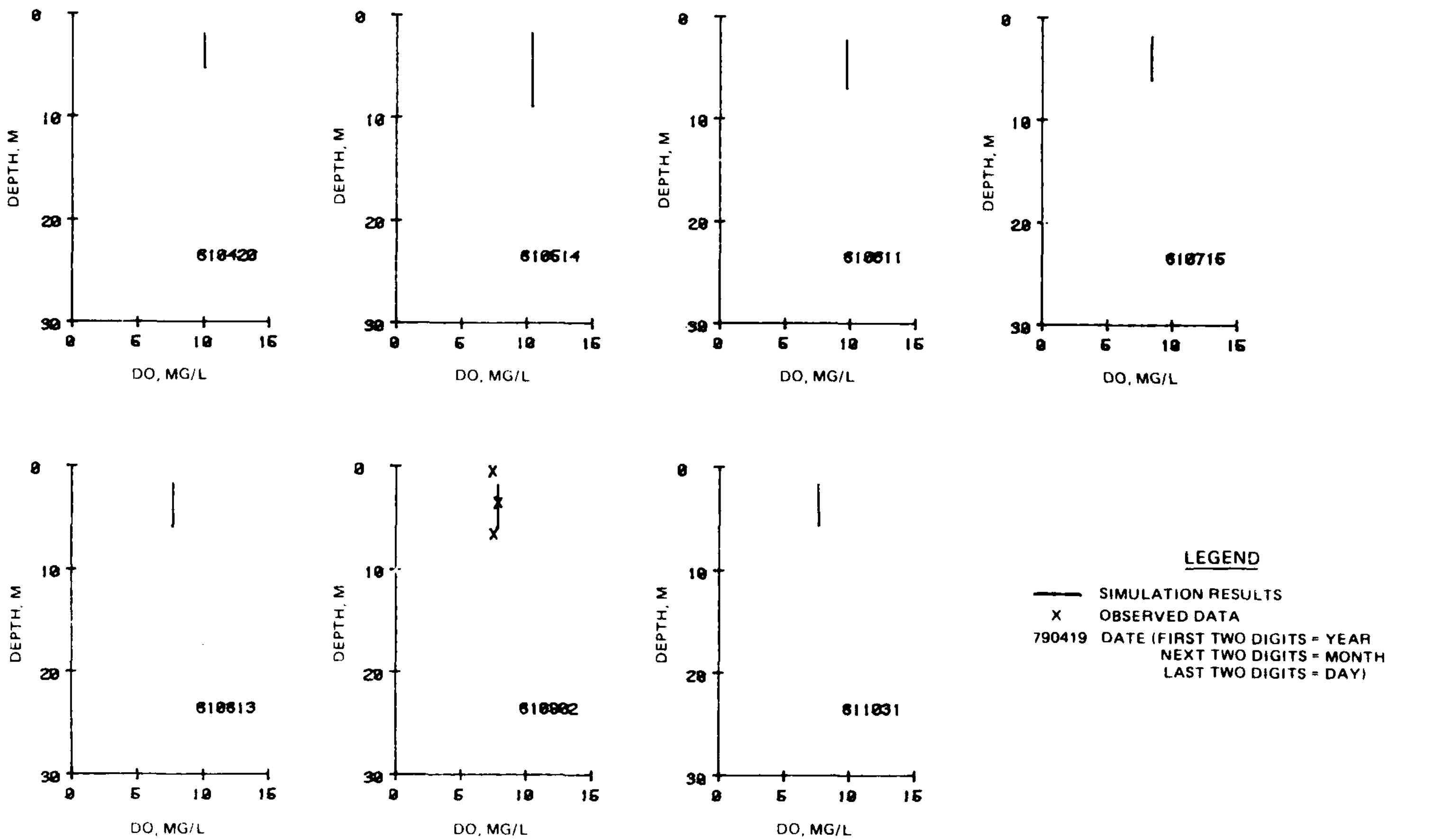
PREDICTED VERSUS OBSERVED TEMPERATURES
RM 328



FINAL VERIFICATION PHASE
PREDICTED VERSUS OBSERVED TEMPERATURES
RM 314

PLATE 18



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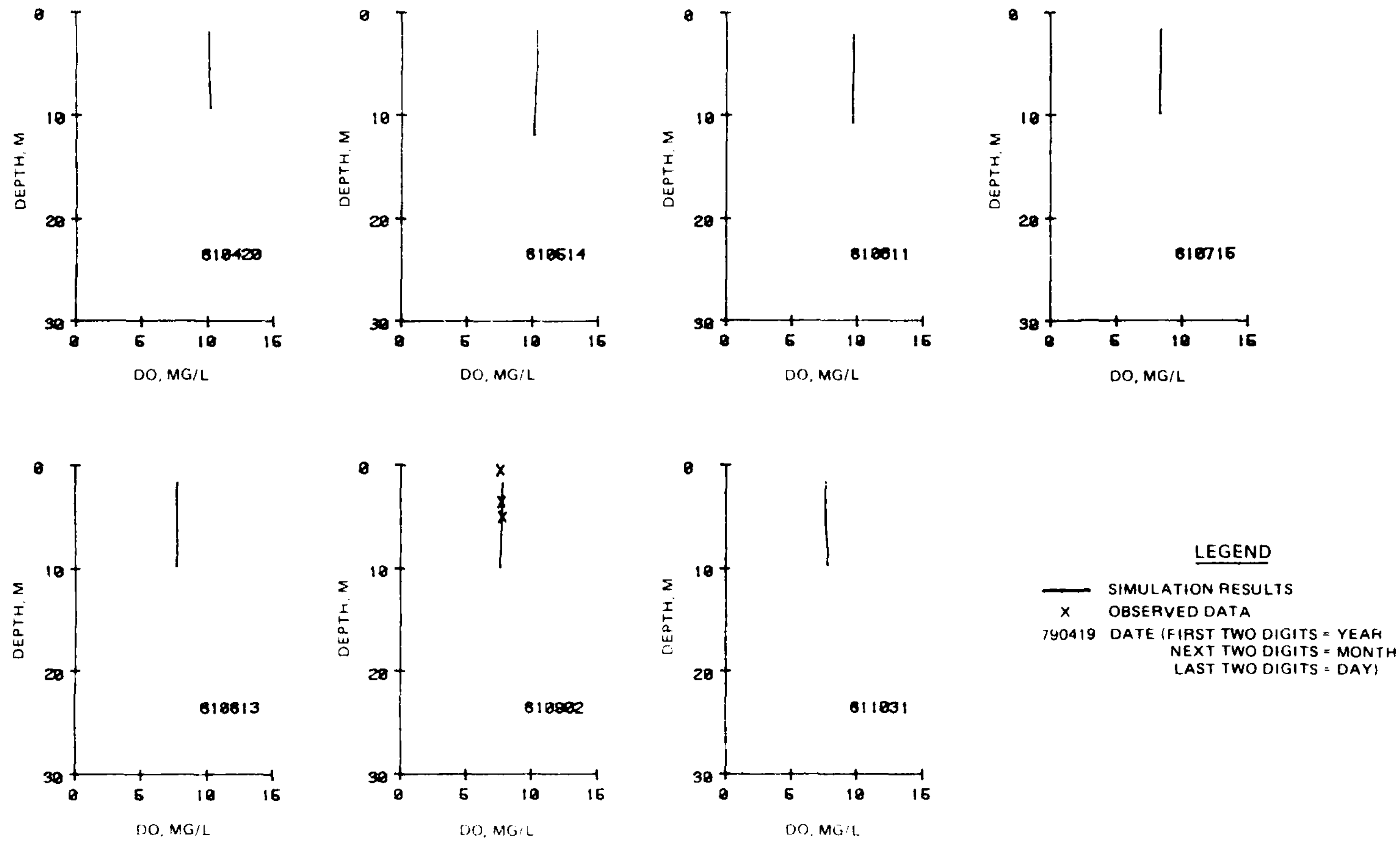
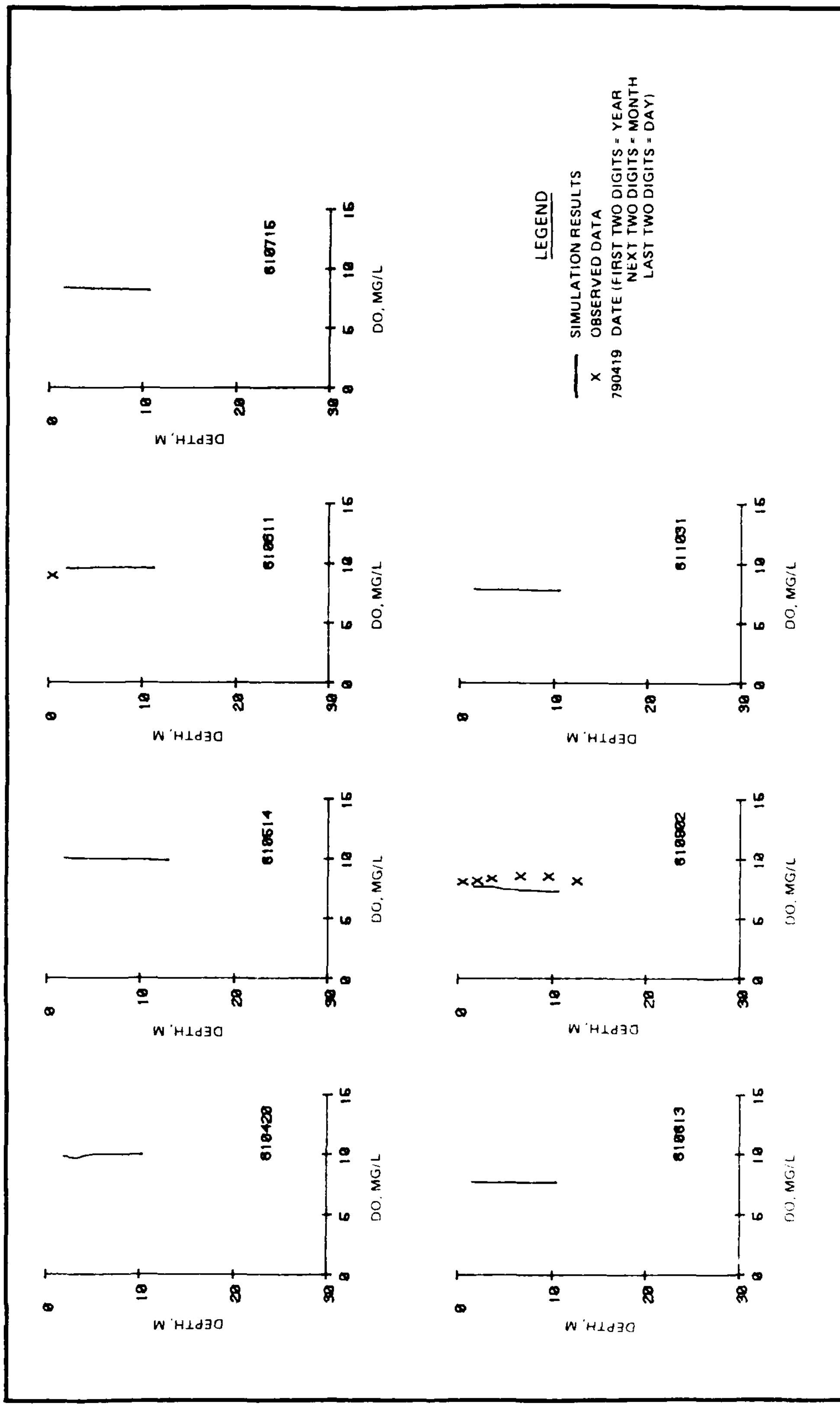
PREDICTED VERSUS OBSERVED DO
RM 380



FINAL VERIFICATION PHASE
PREDICTED VERSUS OBSERVED DO
RM 374

PLATE 20



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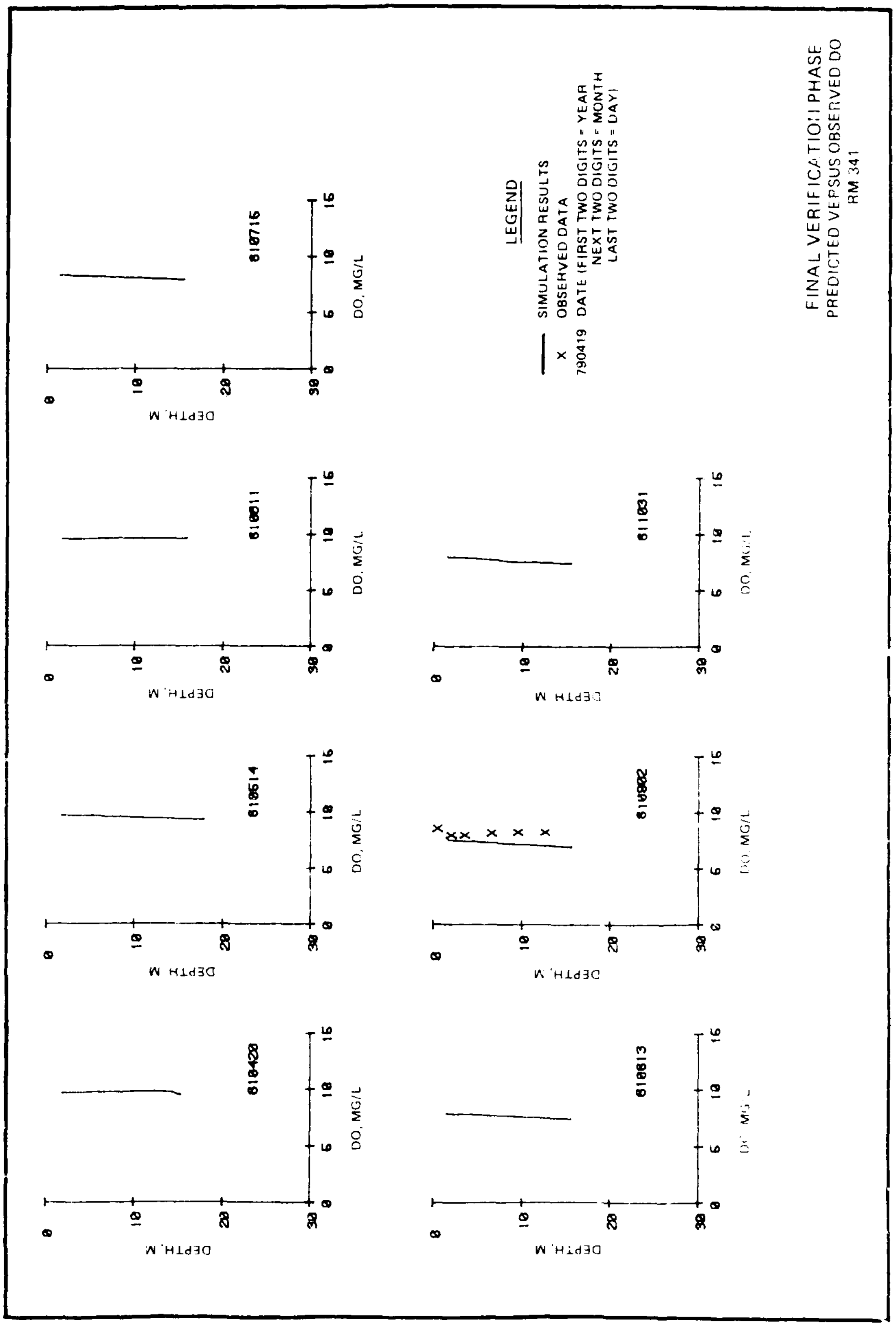
RM 358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PREDICTED VERSUS OBSERVED DO
RM 341
LEGEND
SIMULATION RESULTS
X OBSERVED DATA
790419 DATE (FIRST TWO DIGITS = YEAR
NEXT TWO DIGITS = MONTH
LAST TWO DIGITS = DAY)
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810514
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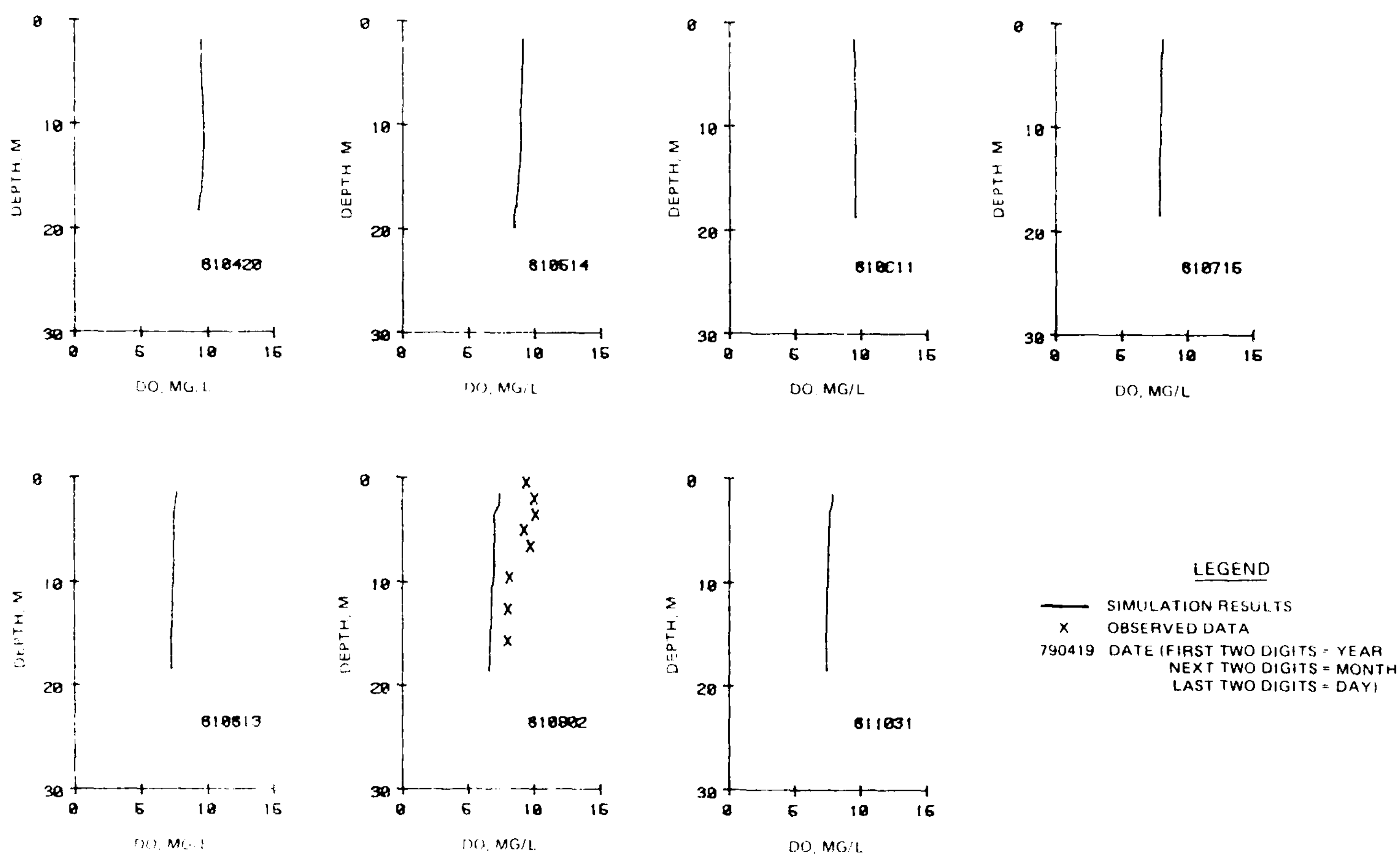
810813
810902
811031
DEPTH, M
DO, MG/L

PLATE 22



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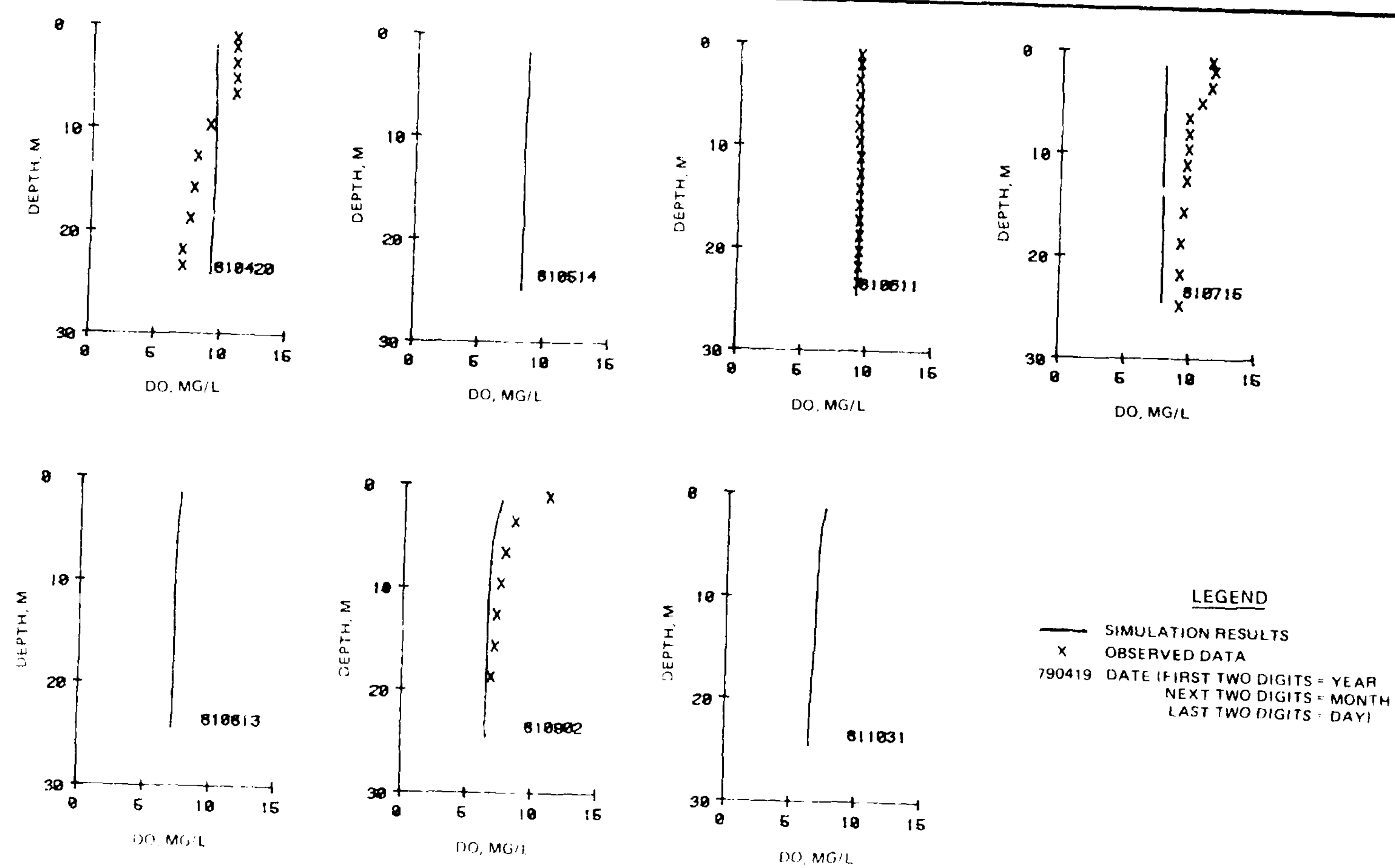
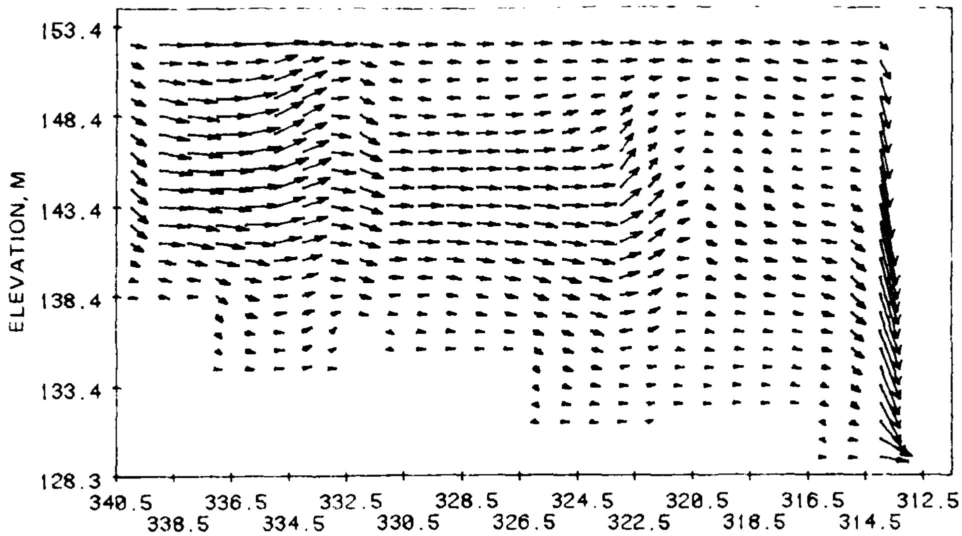
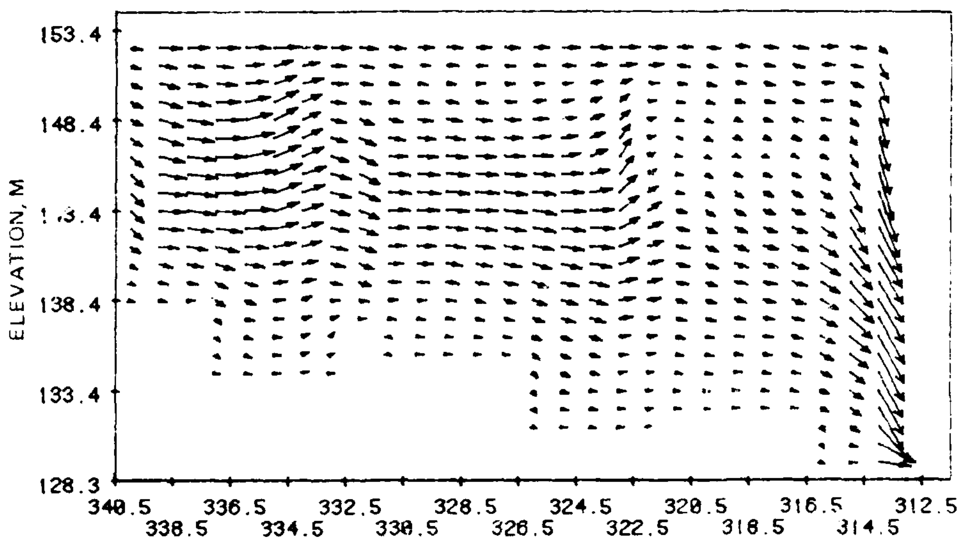


FINAL VERIFICATION PHASE
PREDICTED VERSUS OBSERVED DO
RM 314

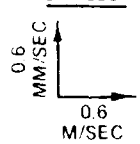
PLATE 24



a. JULIAN DAY 119

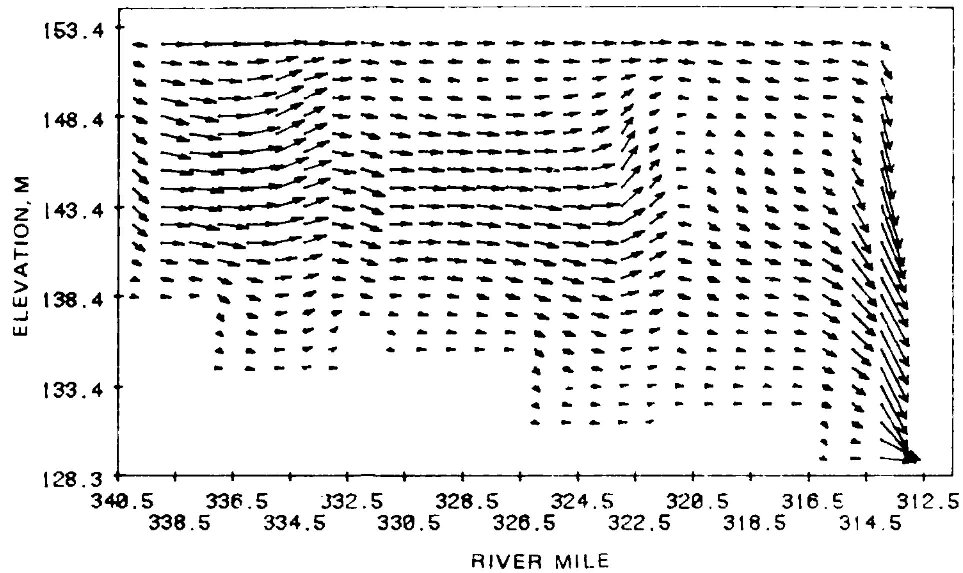


VECTOR SCALES



b. JULIAN DAY 180

WET YEAR (1979) MODEL RESULTS
VELOCITY VECTORS
BRANCH 1
JULIAN DAYS 119 AND 180



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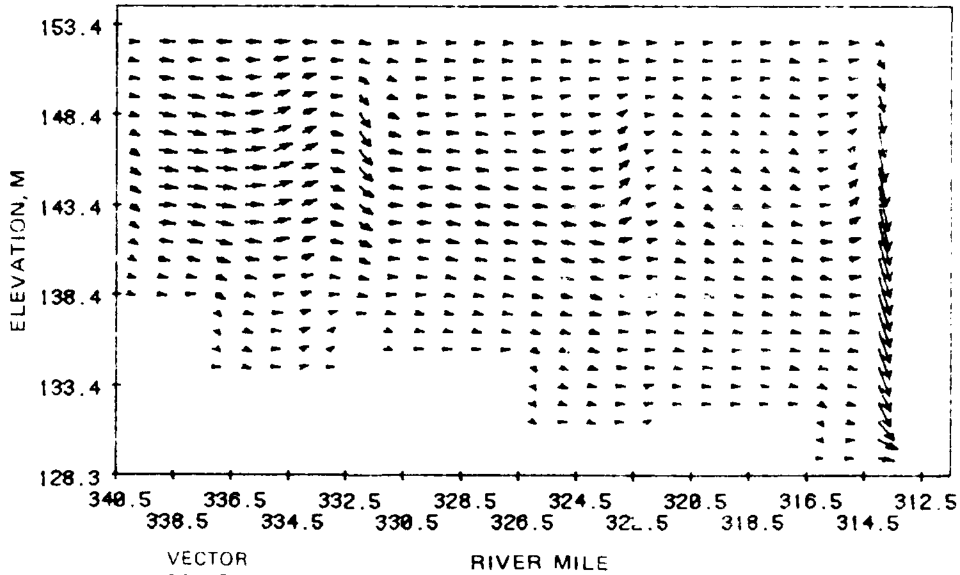
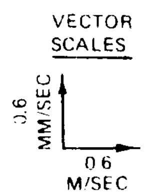
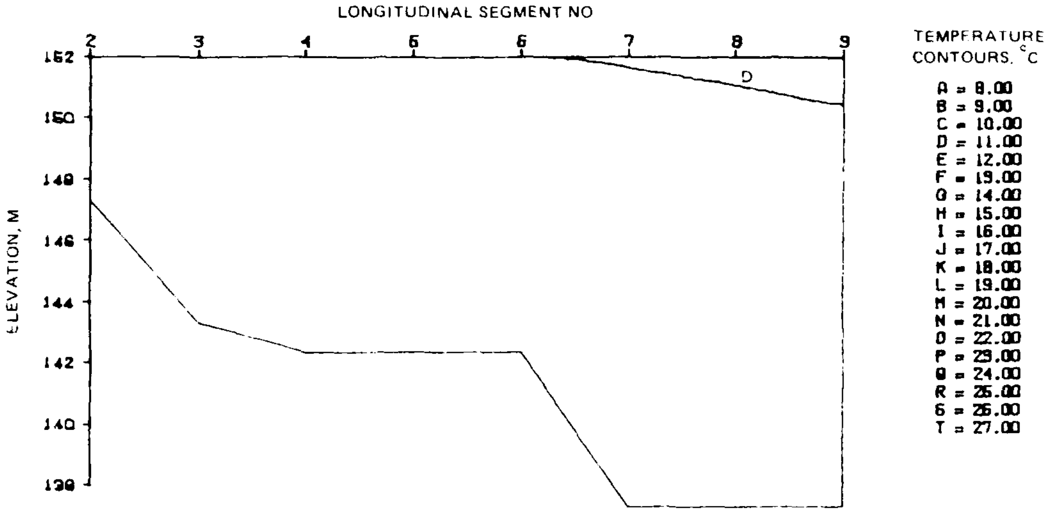


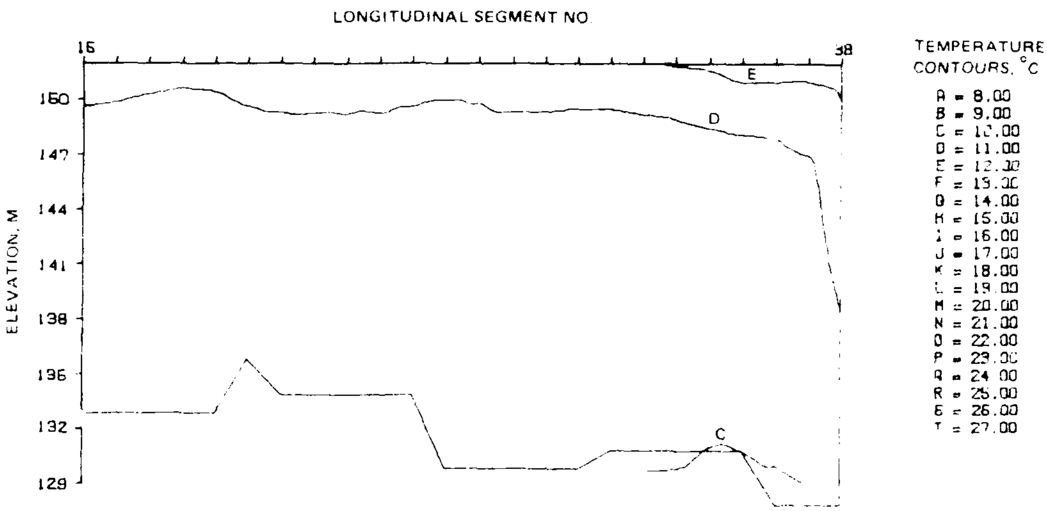


b. JULIAN DAY 302

WET YEAR (1979) MODEL RESULTS
VELOCITY VECTORS
BRANCH 1
JULIAN DAYS 241 AND 302



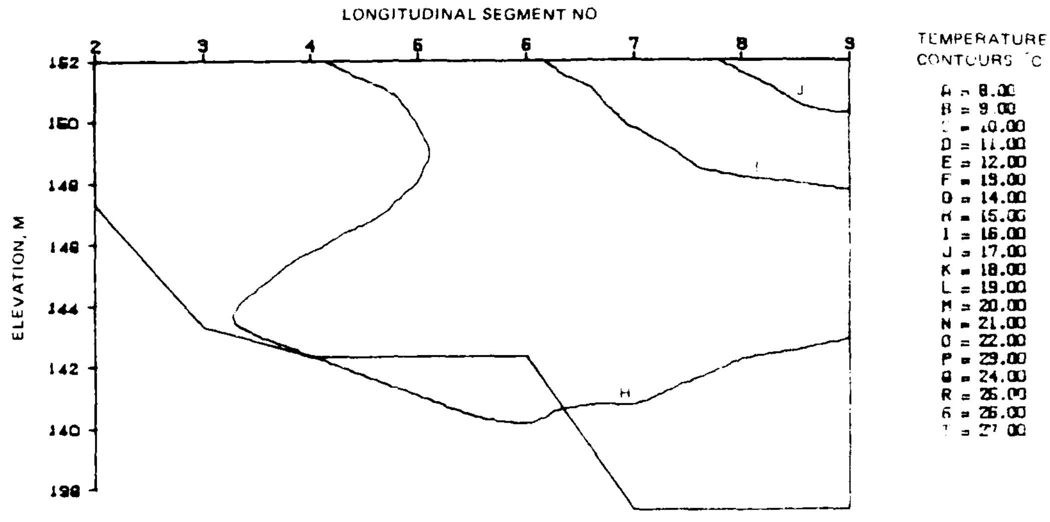
a. BRANCH 2



b. BRANCH 1

WET YEAR (1979) MODEL RESULTS

TEMPERATURE CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 119



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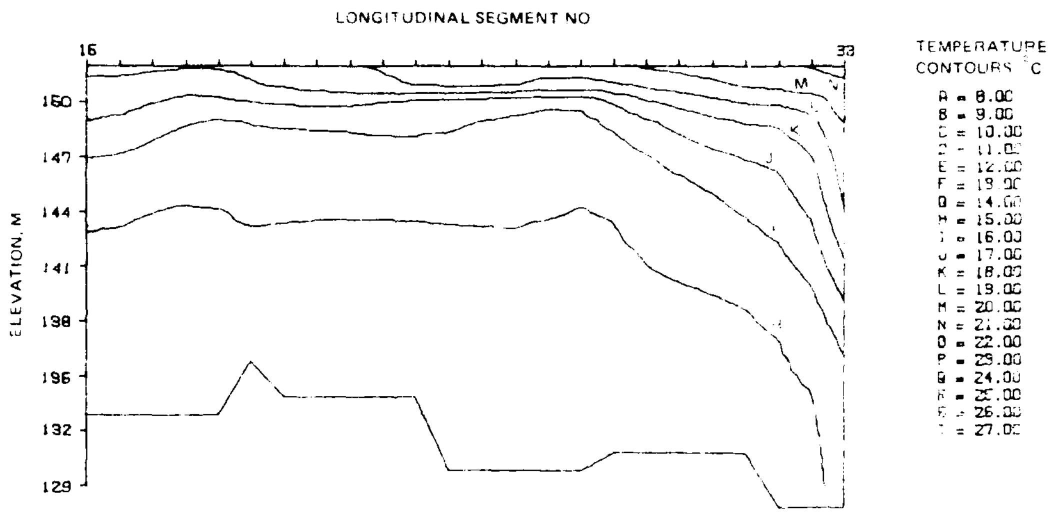
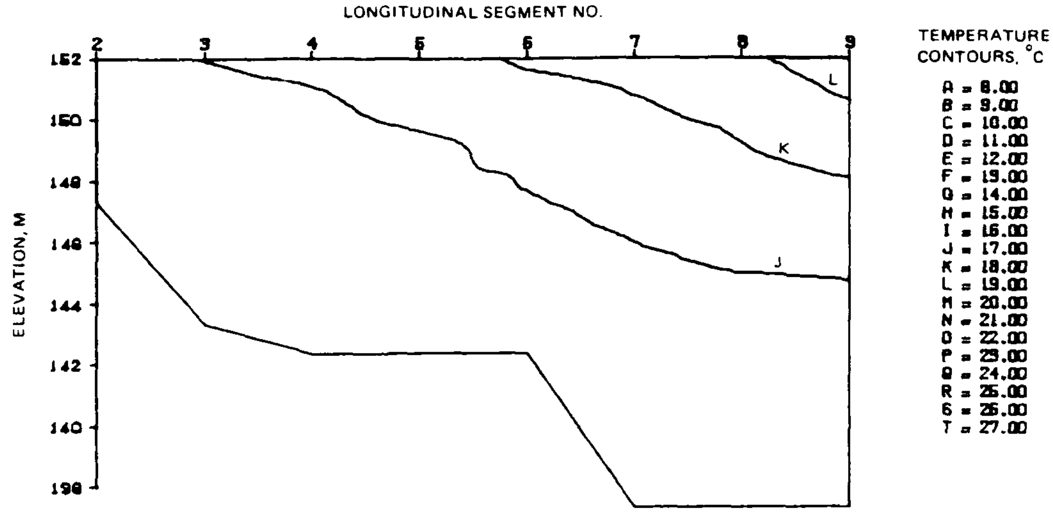


b. BRANCH 1

WET YEAR (1979) MODEL RESULTS
TEMPERATURE CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 180

PLATE 20



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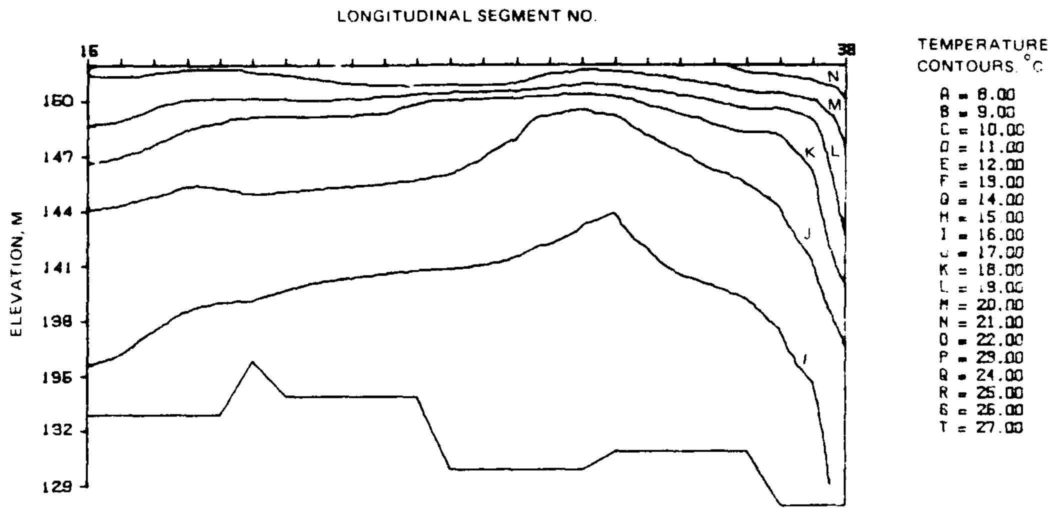
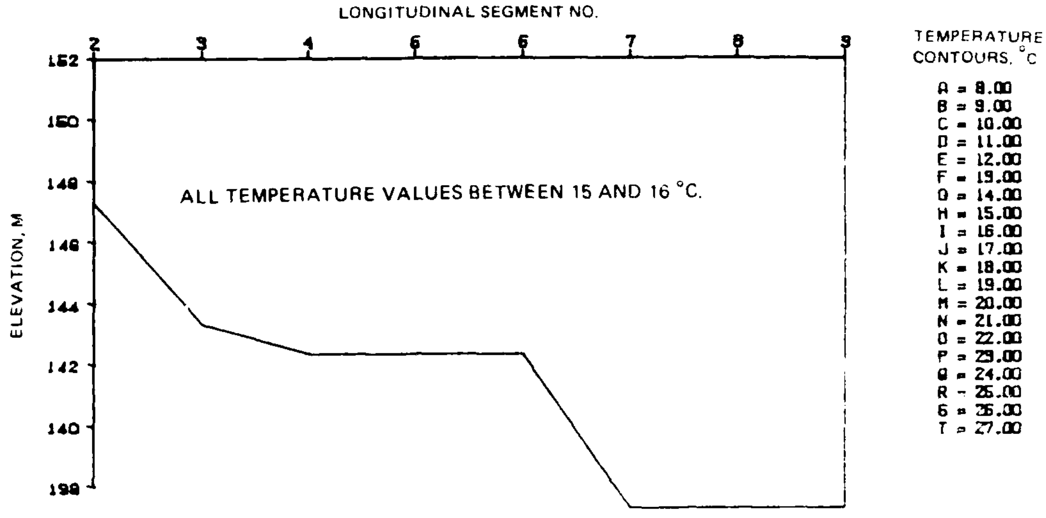


b. BRANCH 1

WET YEAR (1979) MODEL RESULTS
TEMPERATURE CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 241



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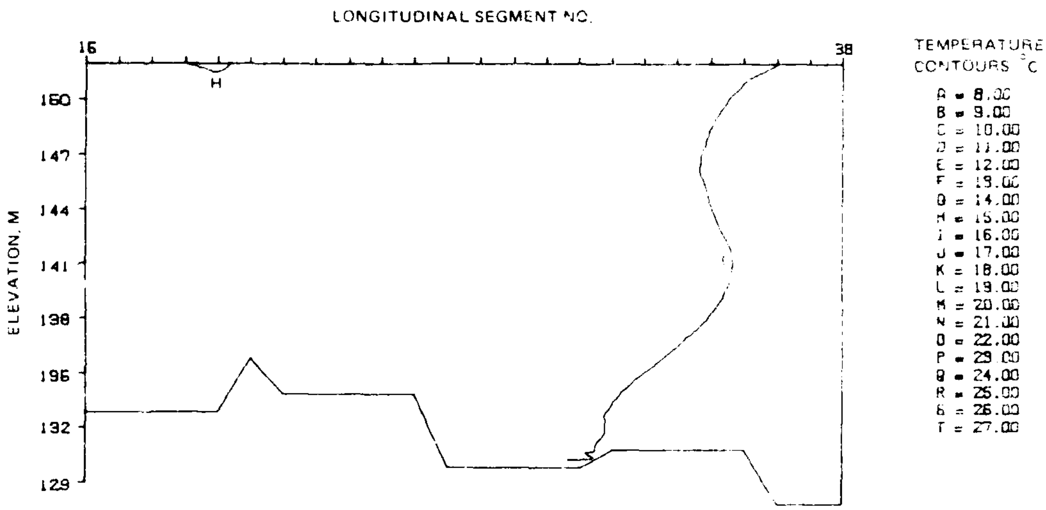
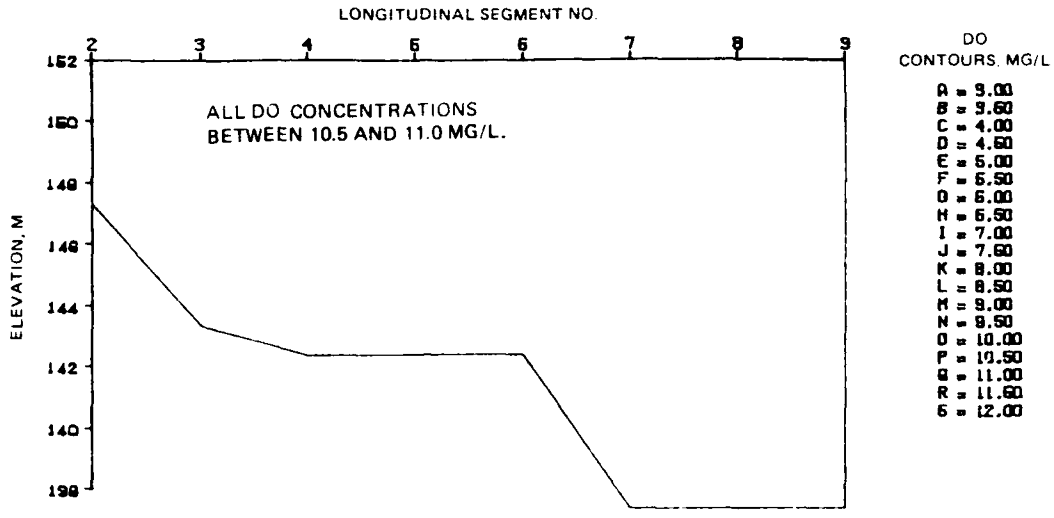


b. BRANCH 1

WET YEAR (1979) MODEL RESULTS
TEMPERATURE CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 302



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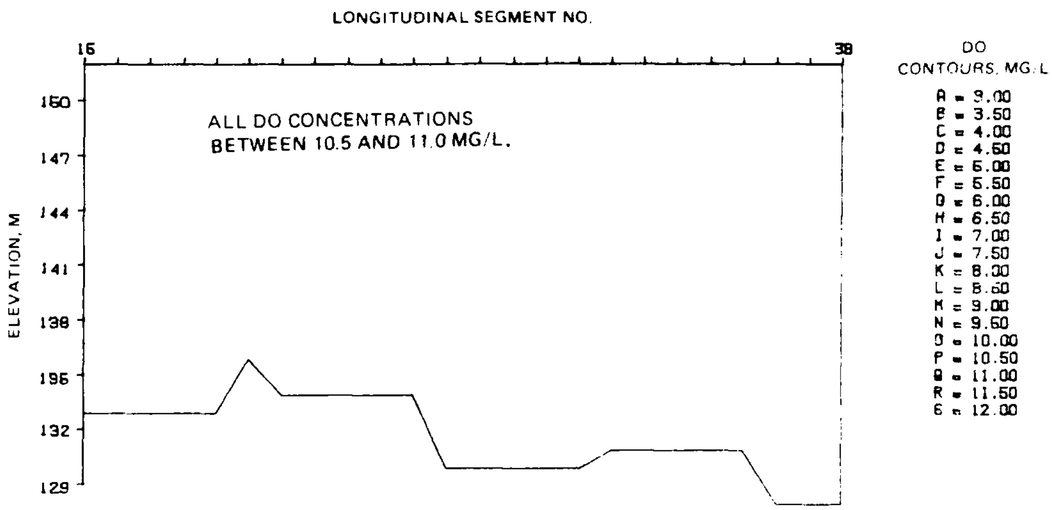
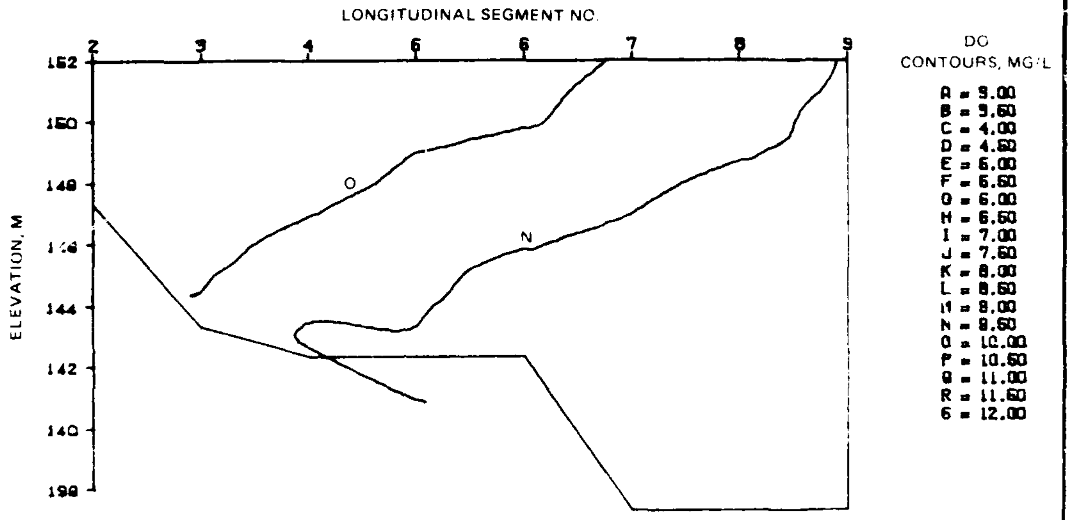
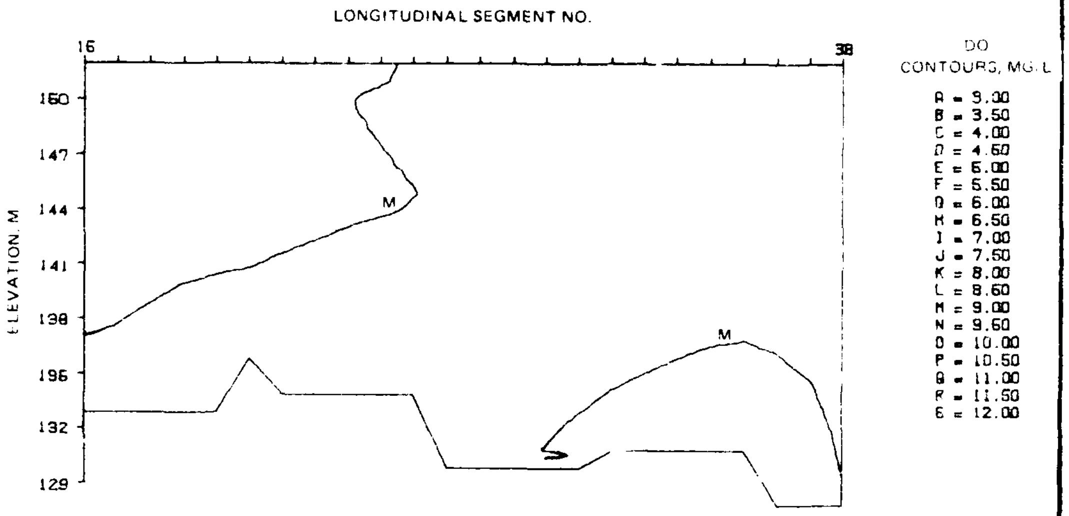


b. BRANCH 1

WET YEAR (1979) MODEL RESULTS
DO CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 119



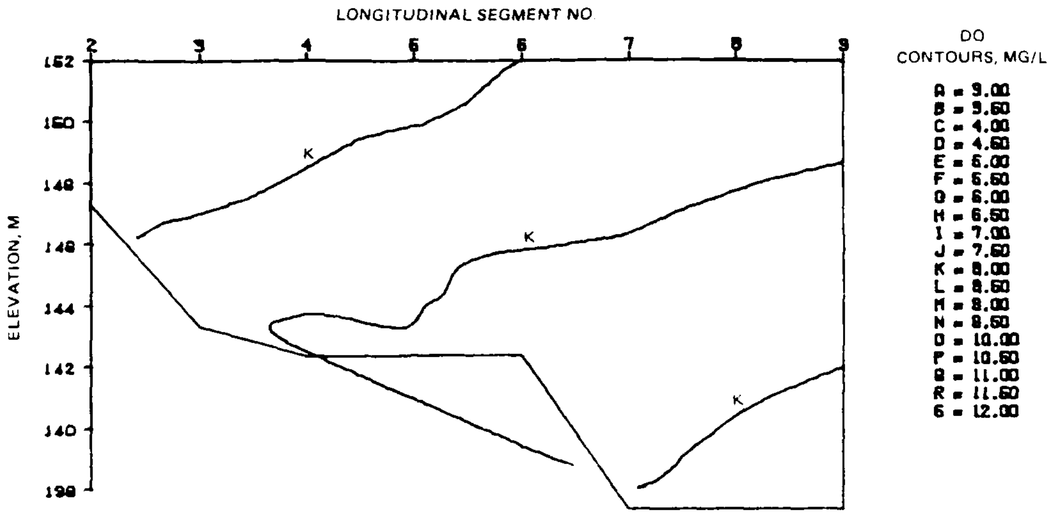
a. BRANCH 2



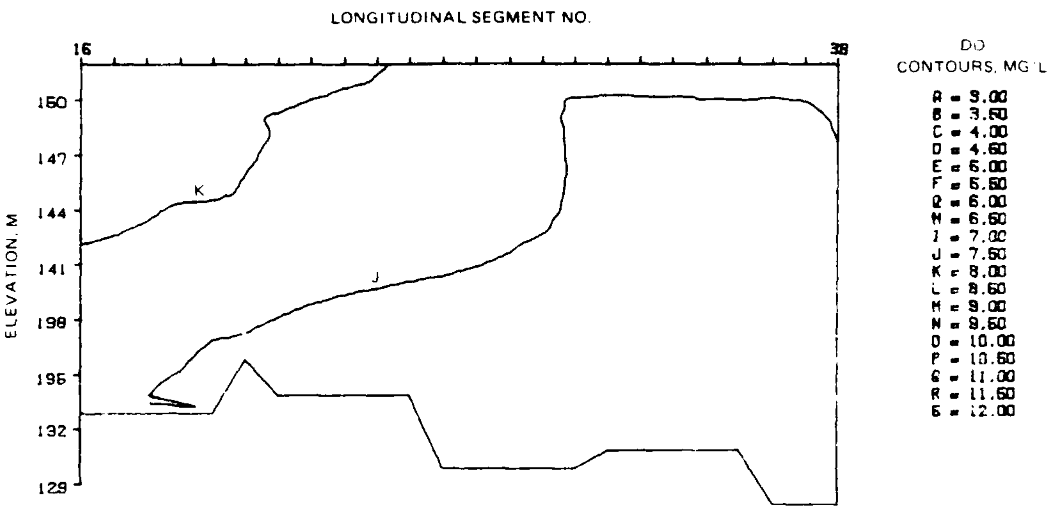
b. BRANCH 1

WET YEAR (1979) MODEL RESULTS
DO CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 180

PLATE 32

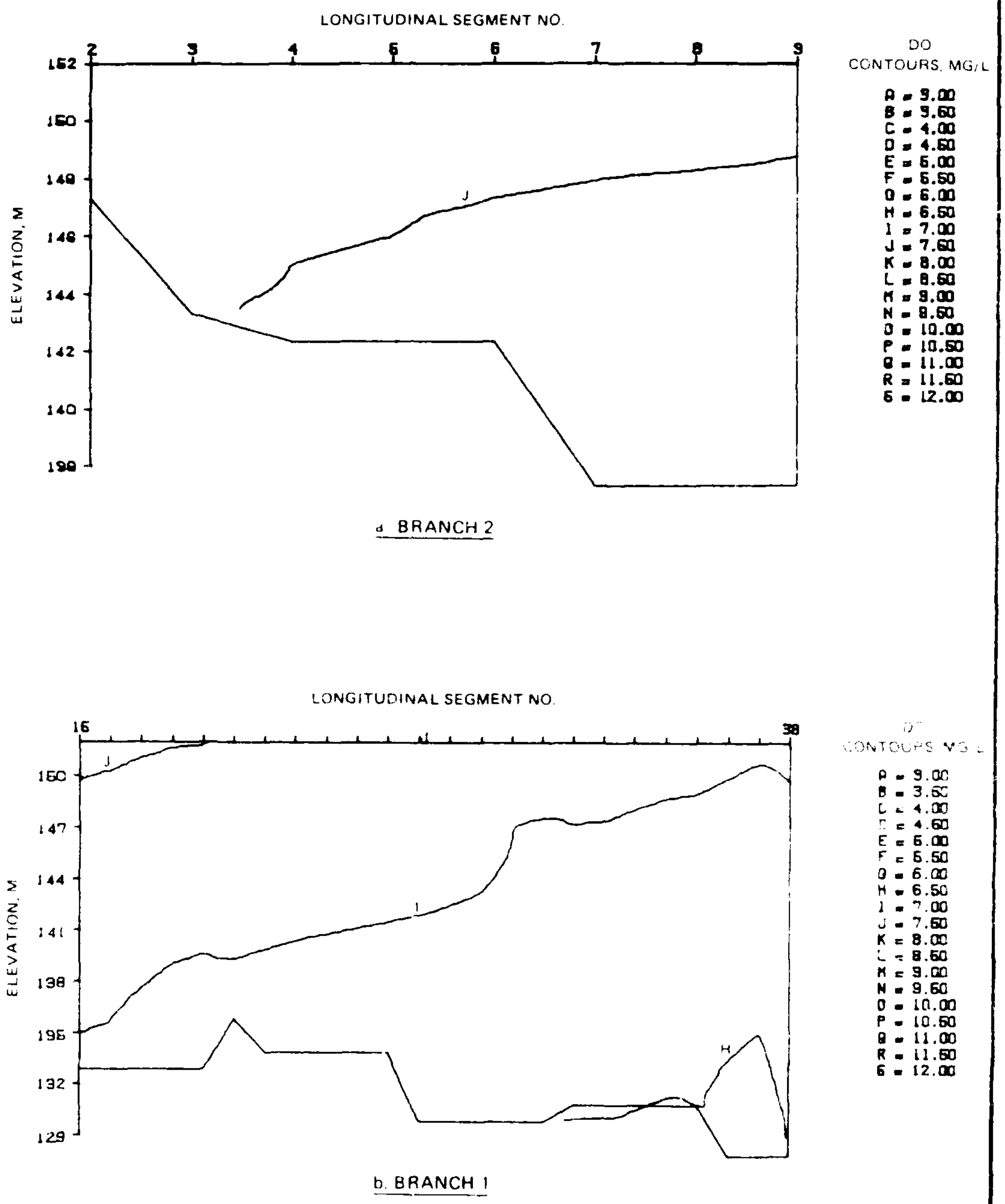


a. BRANCH 2



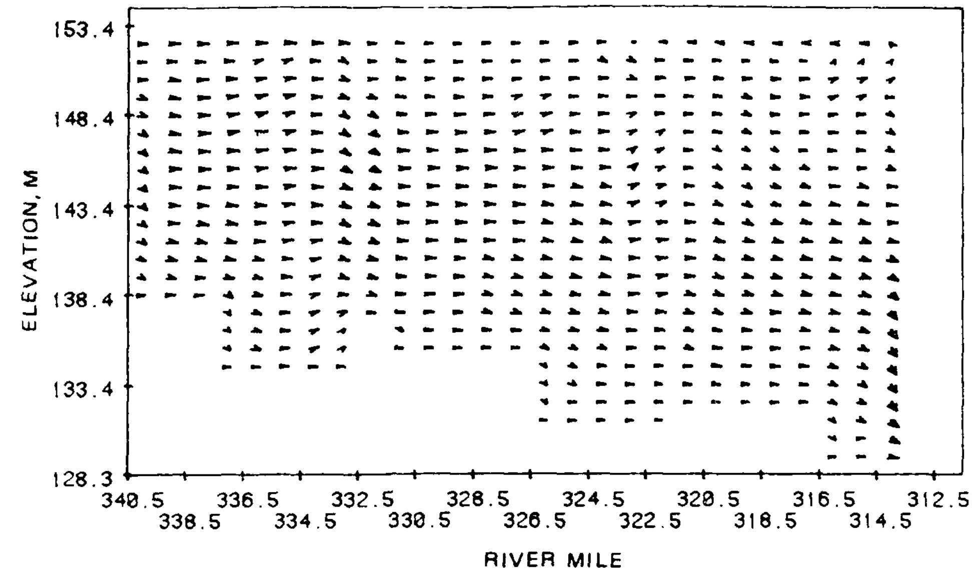
b. BRANCH 1

WET YEAR (1979) MODEL RESULTS
DO CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 241

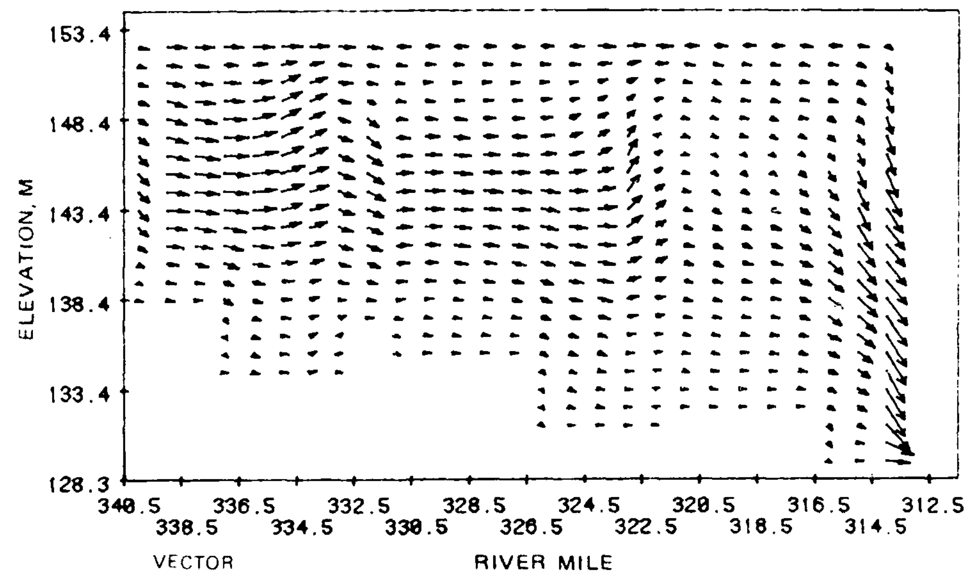


WET YEAR (1979) MODEL RESULTS
DO CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 302

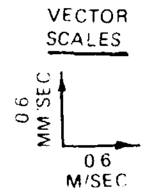
PLATE 34



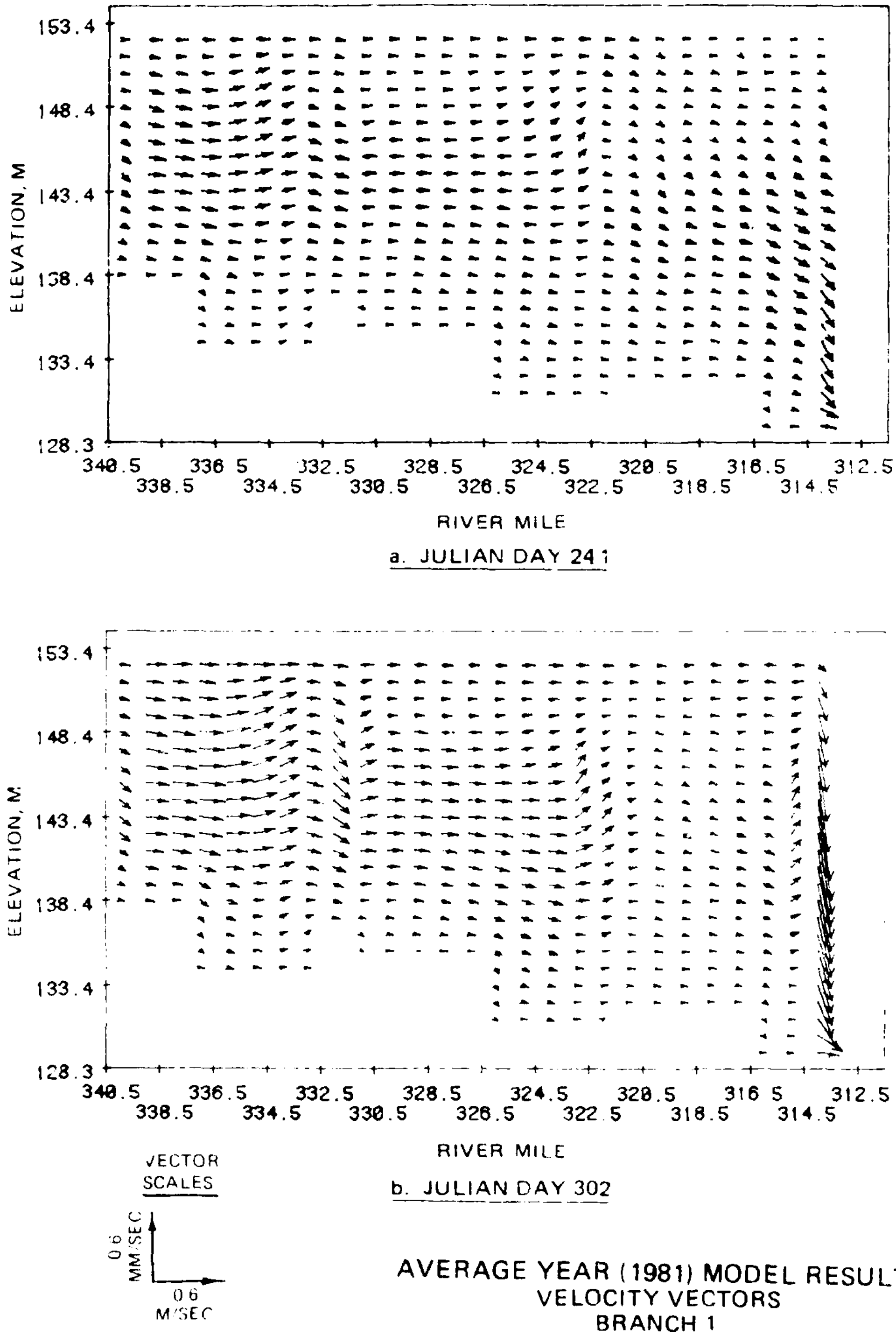
a. JULIAN DAY 119



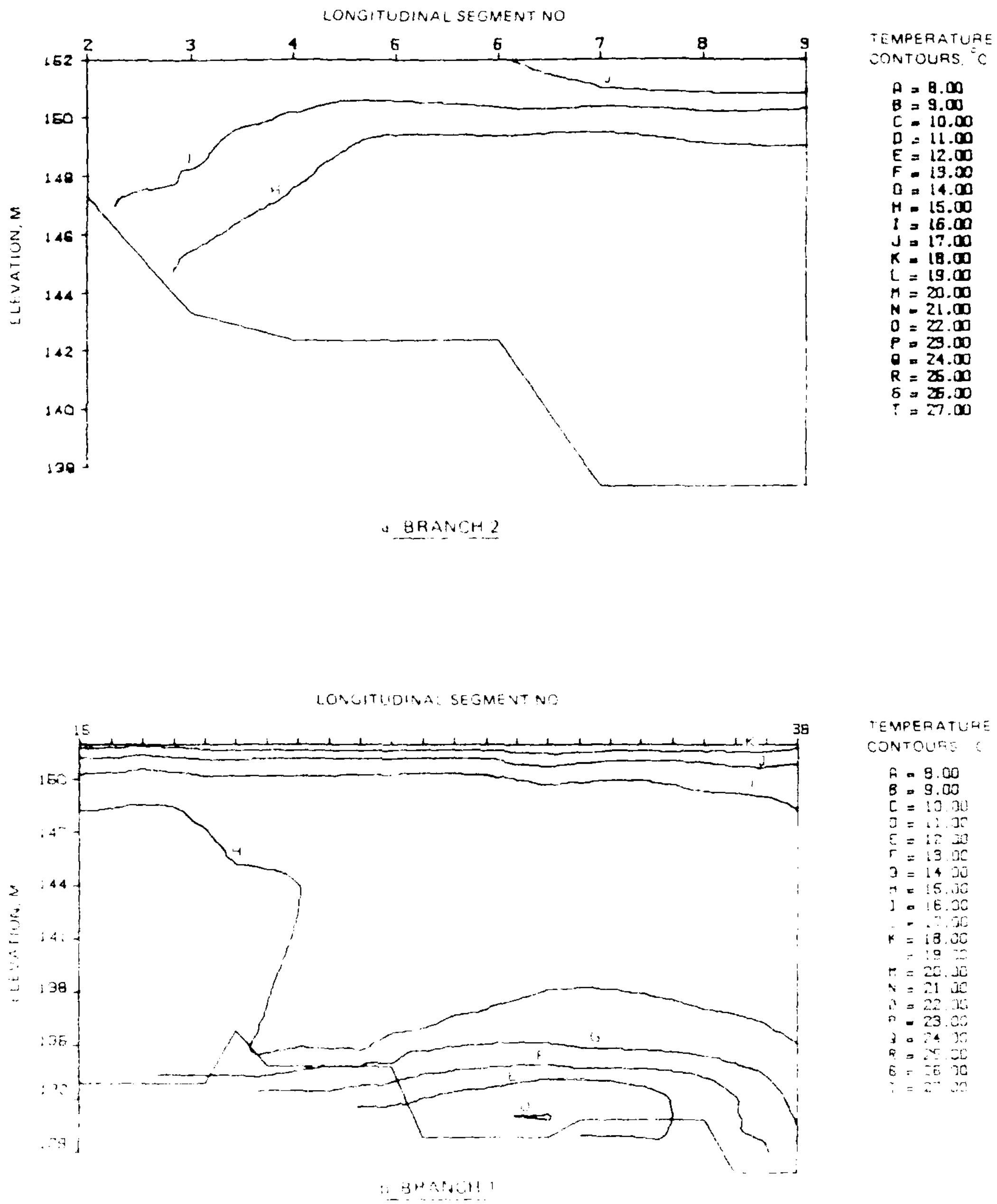
b. JULIAN DAY 180



AVERAGE YEAR (1981) MODEL RESULTS
VELOCITY VECTORS
BRANCH 1
JULIAN DAYS 119 AND 180



AVERAGE YEAR (1981) MODEL RESULTS
VELOCITY VECTORS
BRANCH 1
JULIAN DAYS 241 AND 302

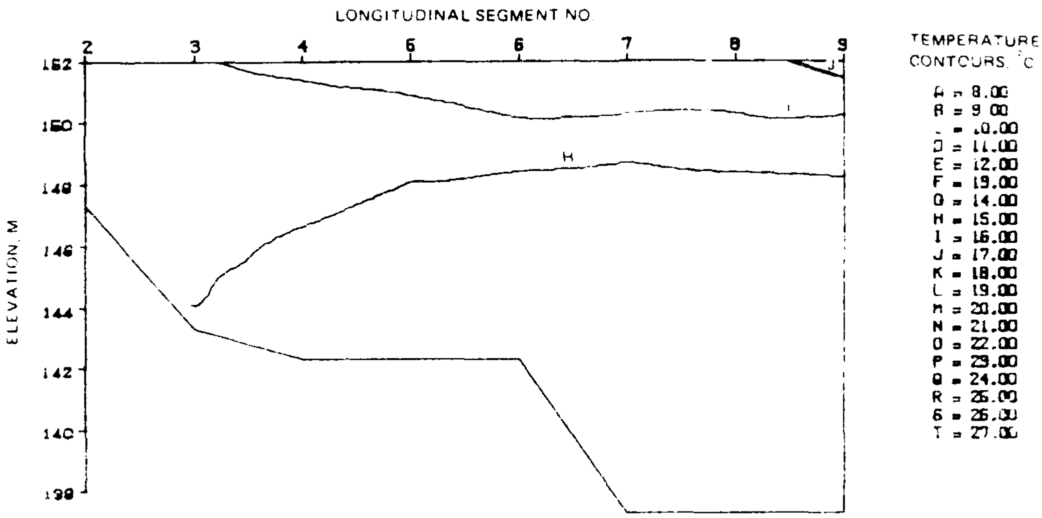


AVERAGE YEAR (1981) MODEL RESULTS

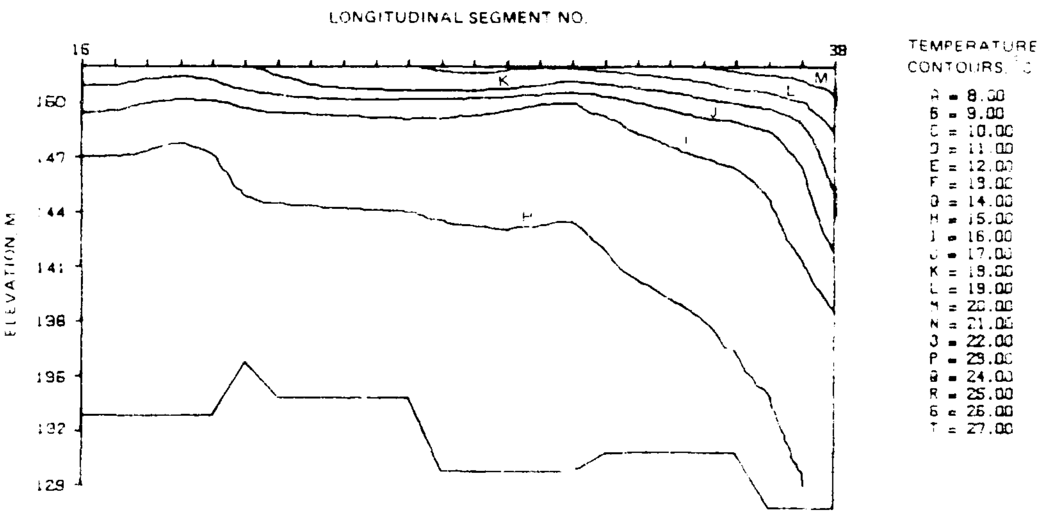
TEMPERATURE CONTOURS

BRANCHES 1 AND 2

JULIAN DAY 119



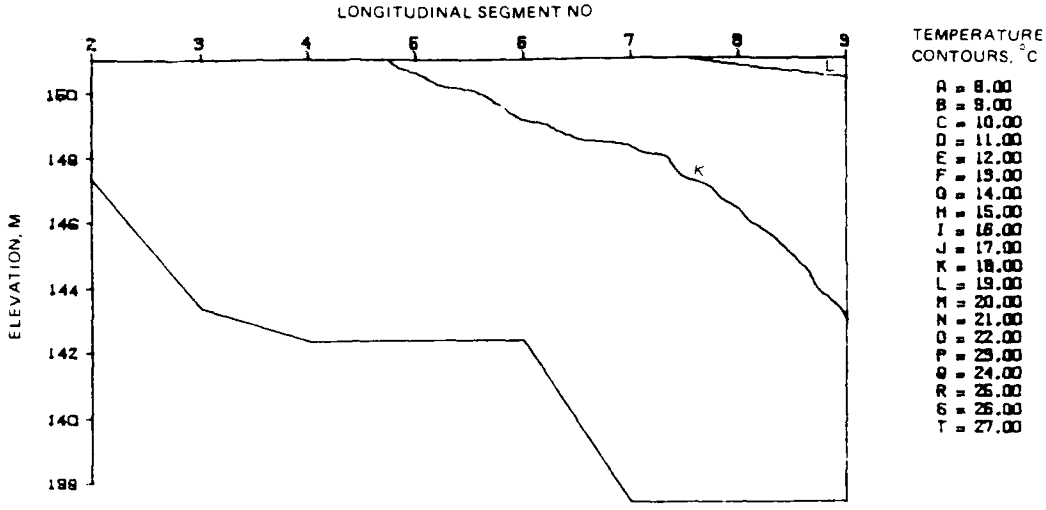
a. BRANCH 2



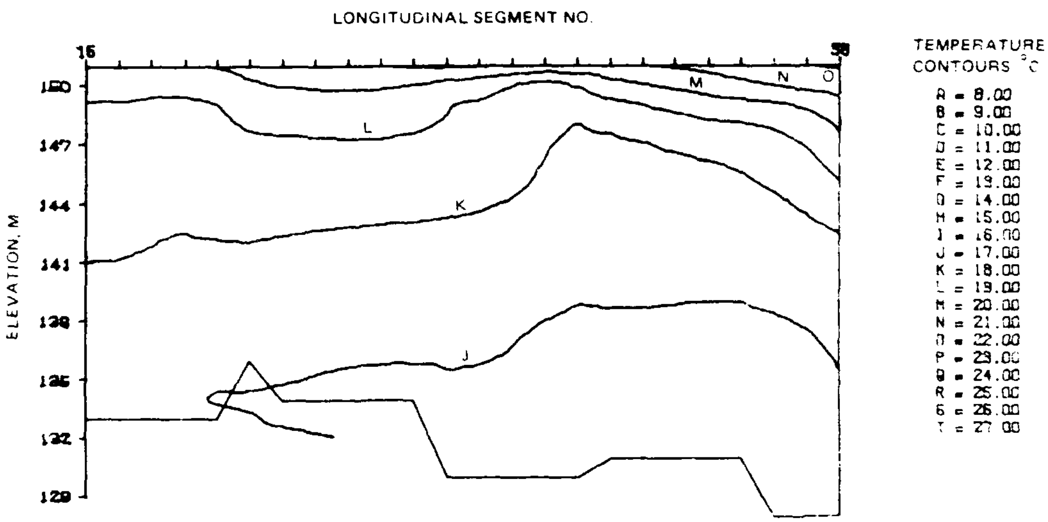
b. BRANCH 1

AVERAGE YEAR (1981) MODEL RESULTS
TEMPERATURE CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 180

PLATE 38



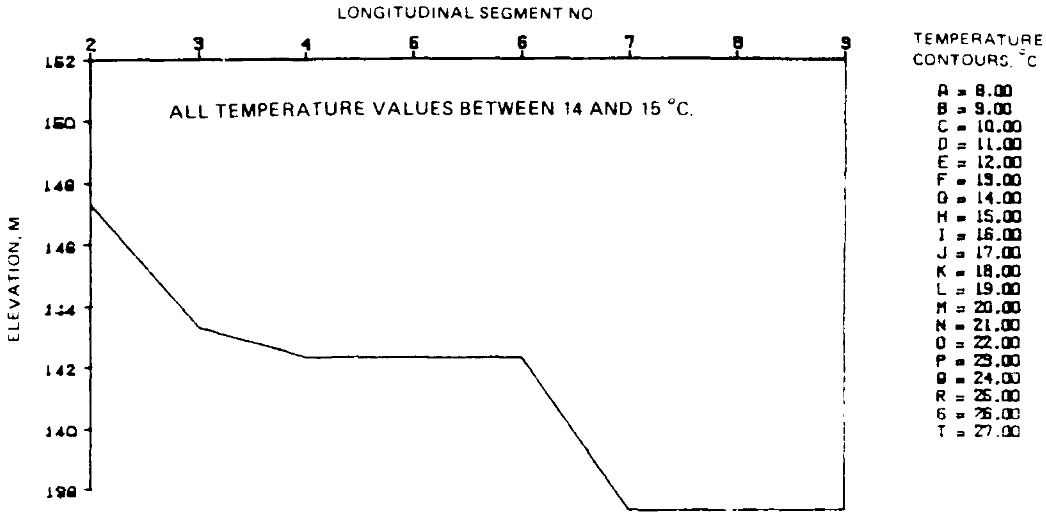
a. BRANCH 2



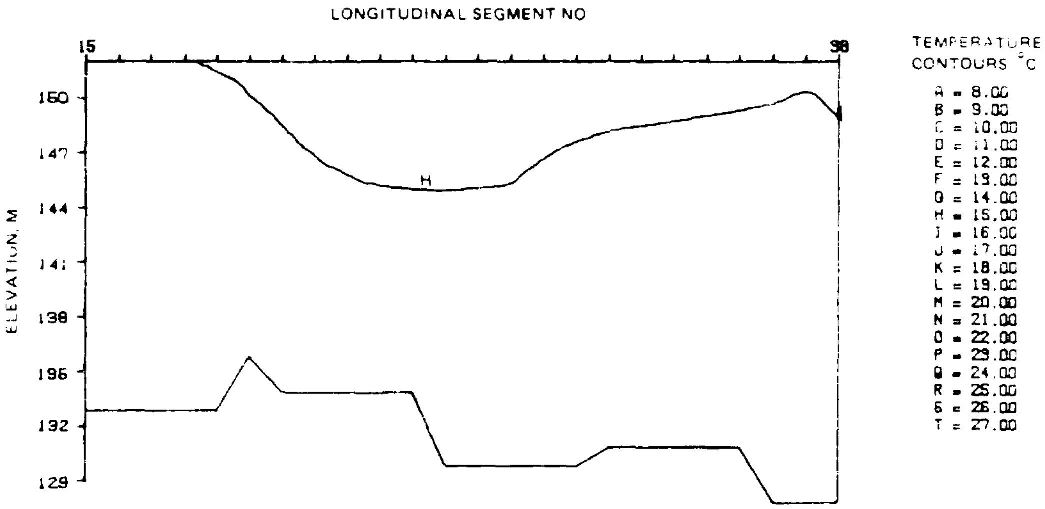
b. BRANCH 1

AVERAGE YEAR (1981) MODEL RESULTS

TEMPERATURE CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 241



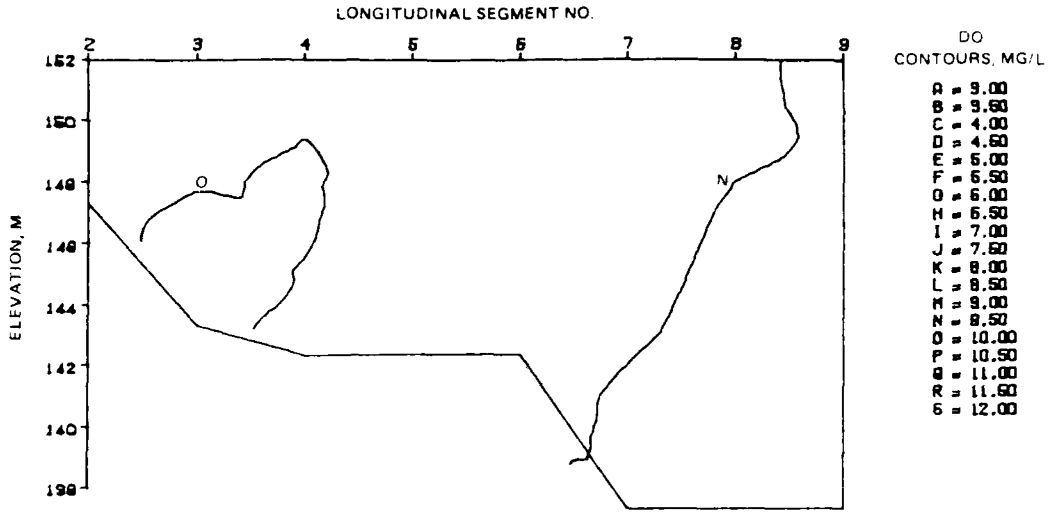
a. BRANCH 2



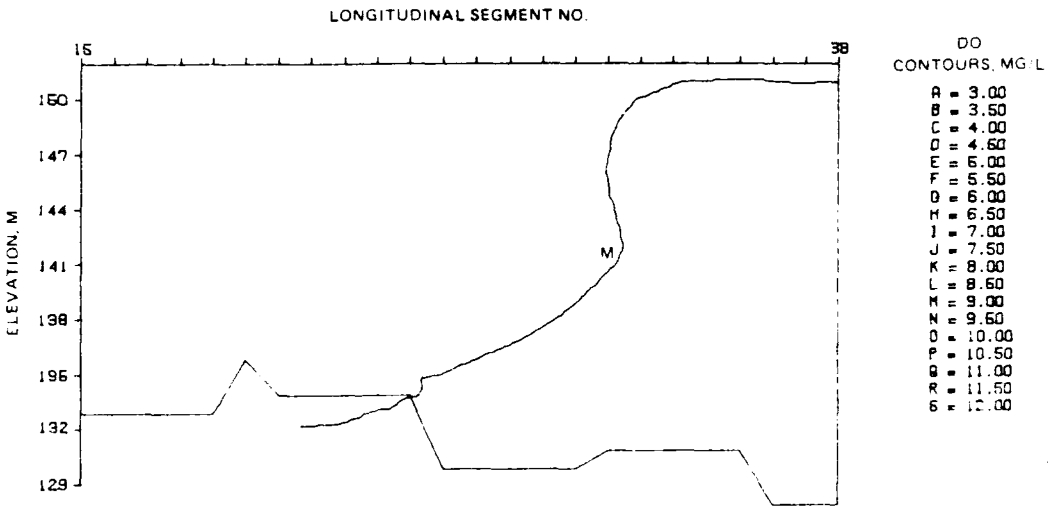
b. BRANCH 1

AVERAGE YEAR (1981) MODEL RESULTS
TEMPERATURE CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 302

PLATE 40



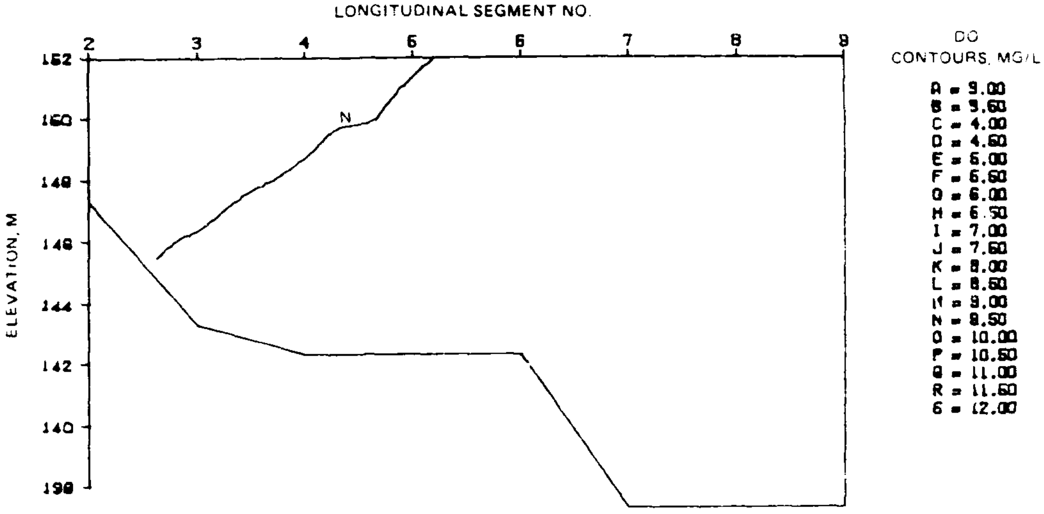
a. BRANCH 2



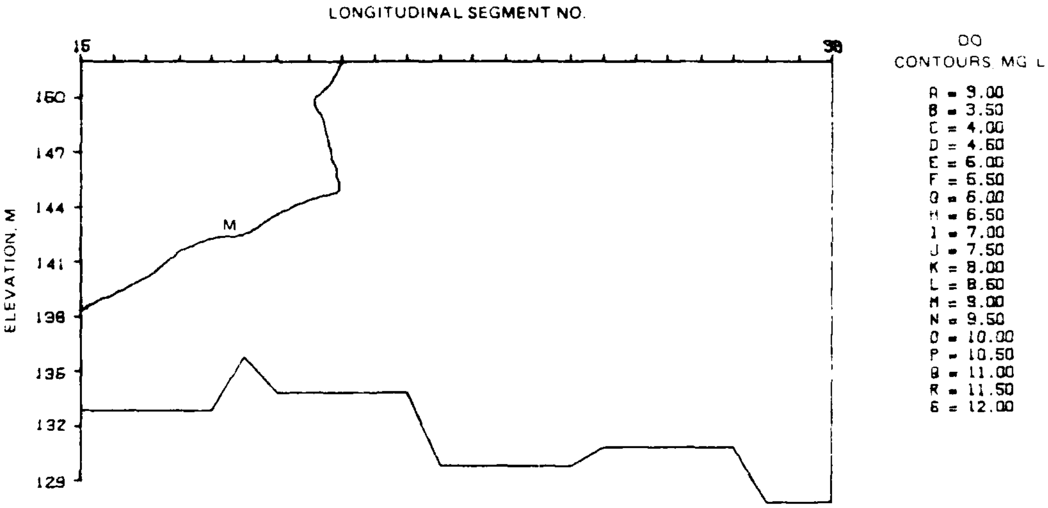
b. BRANCH 1

AVERAGE YEAR (1981) MODEL RESULTS
DO CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 119

PLATE 41



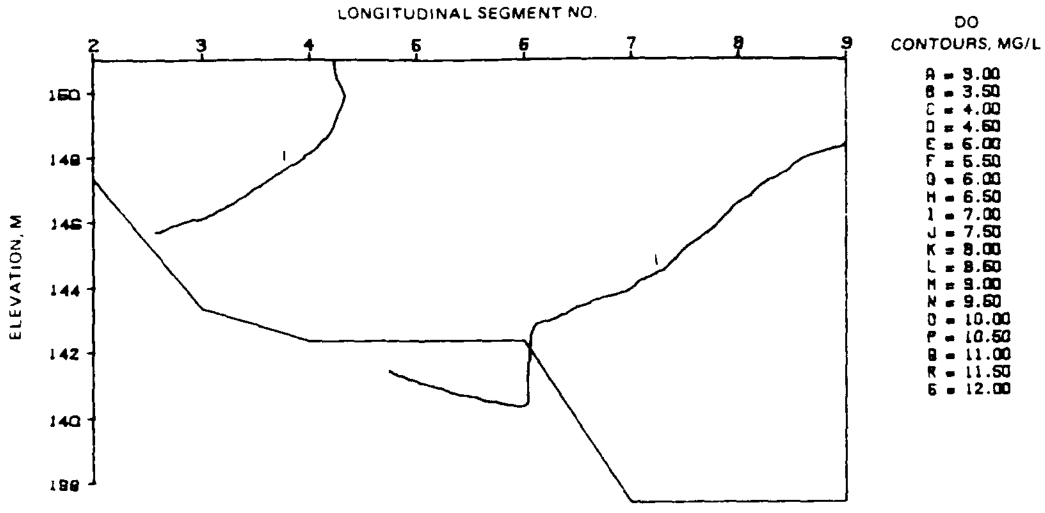
a. BRANCH 2



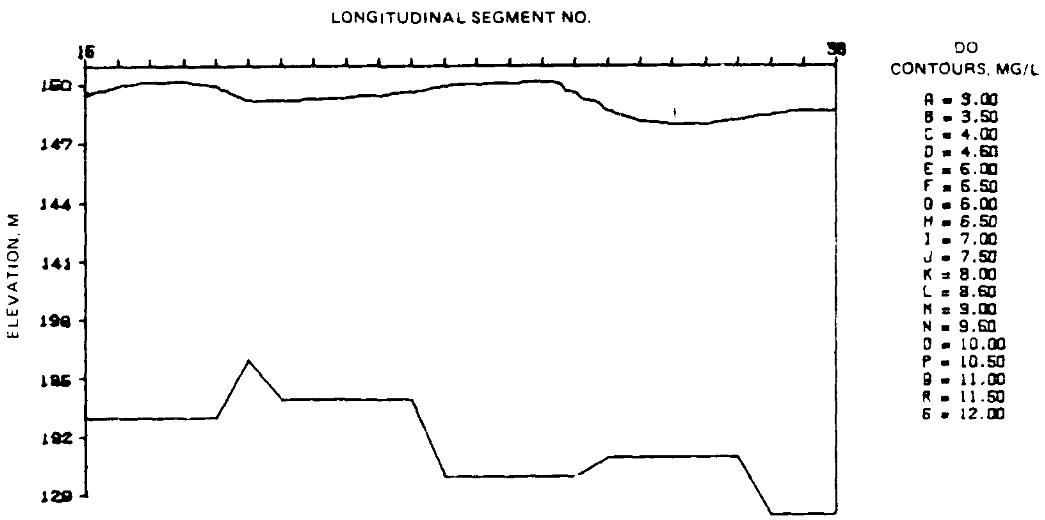
b. BRANCH 1

AVERAGE YEAR (1981) MODEL RESULTS
DO CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 180

PLATE 42

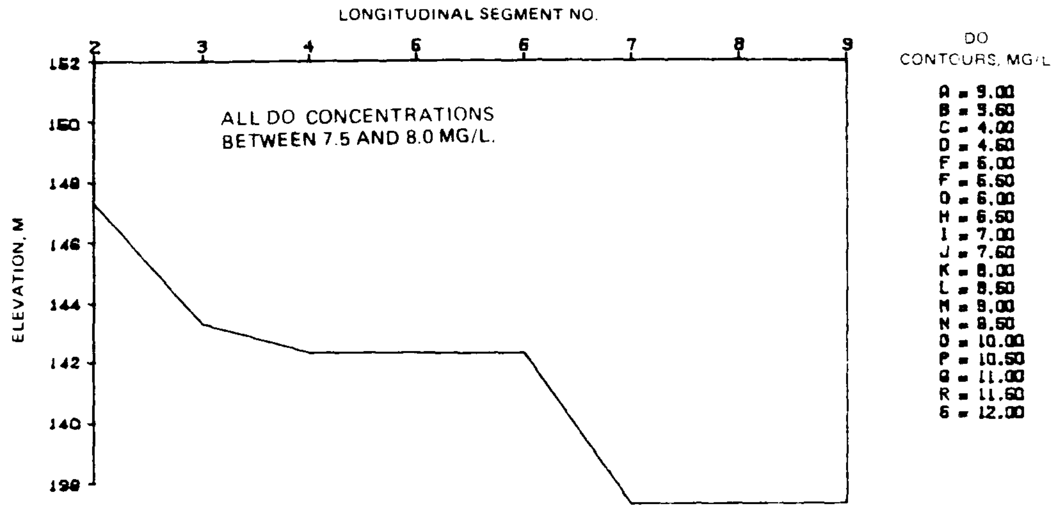


a. BRANCH 2

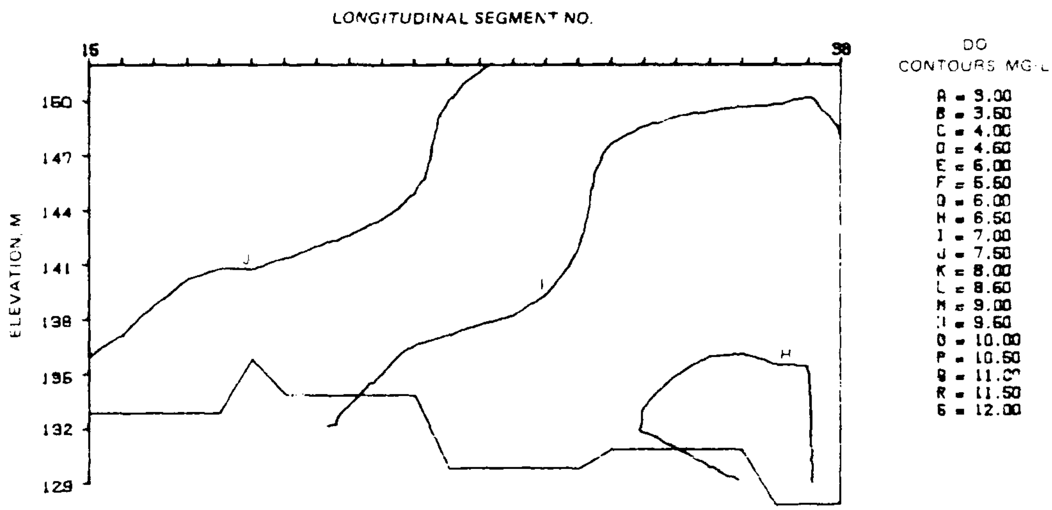


b. BRANCH 1

AVERAGE YEAR (1981) MODEL RESULTS
DO CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 241



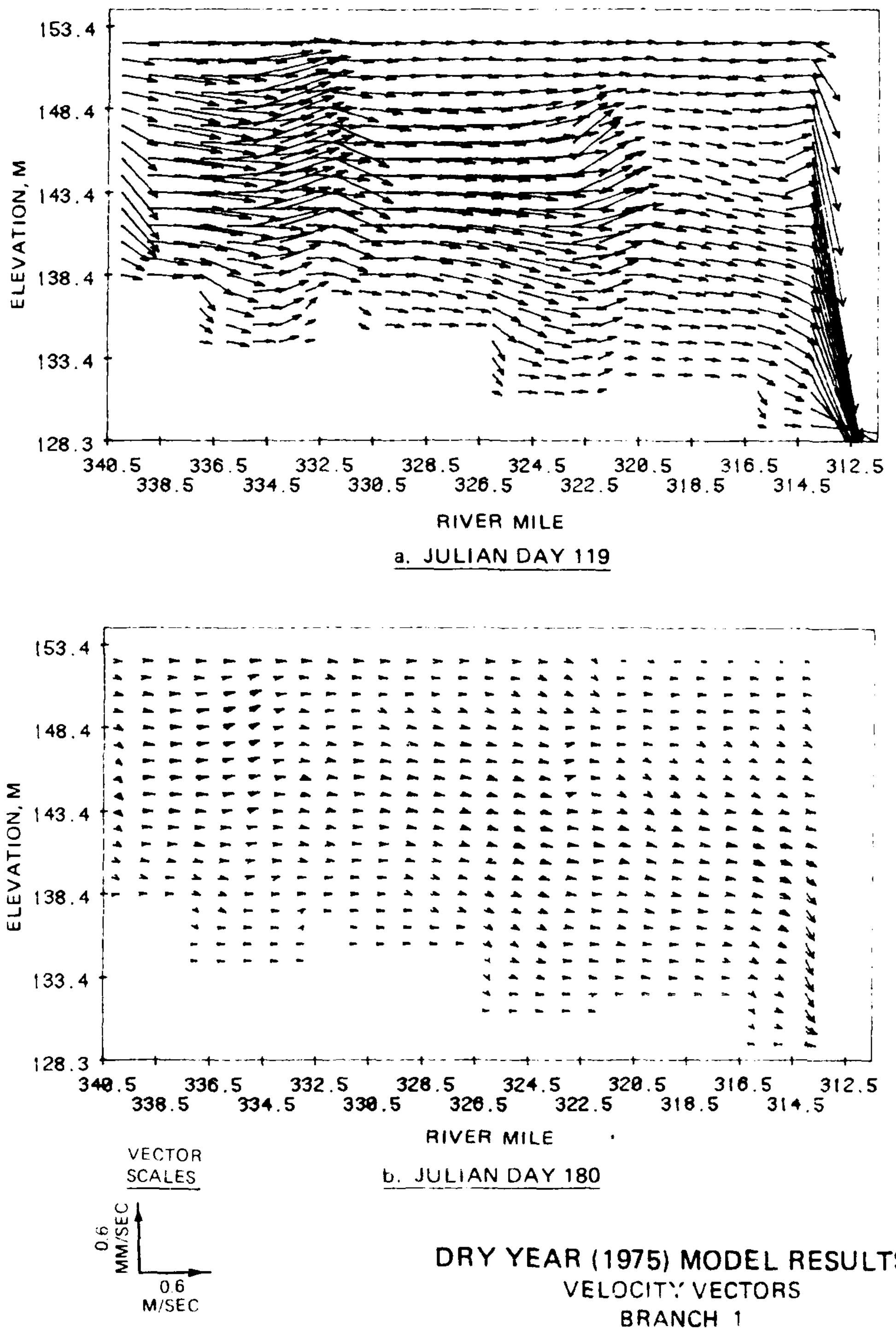
a. BRANCH 2



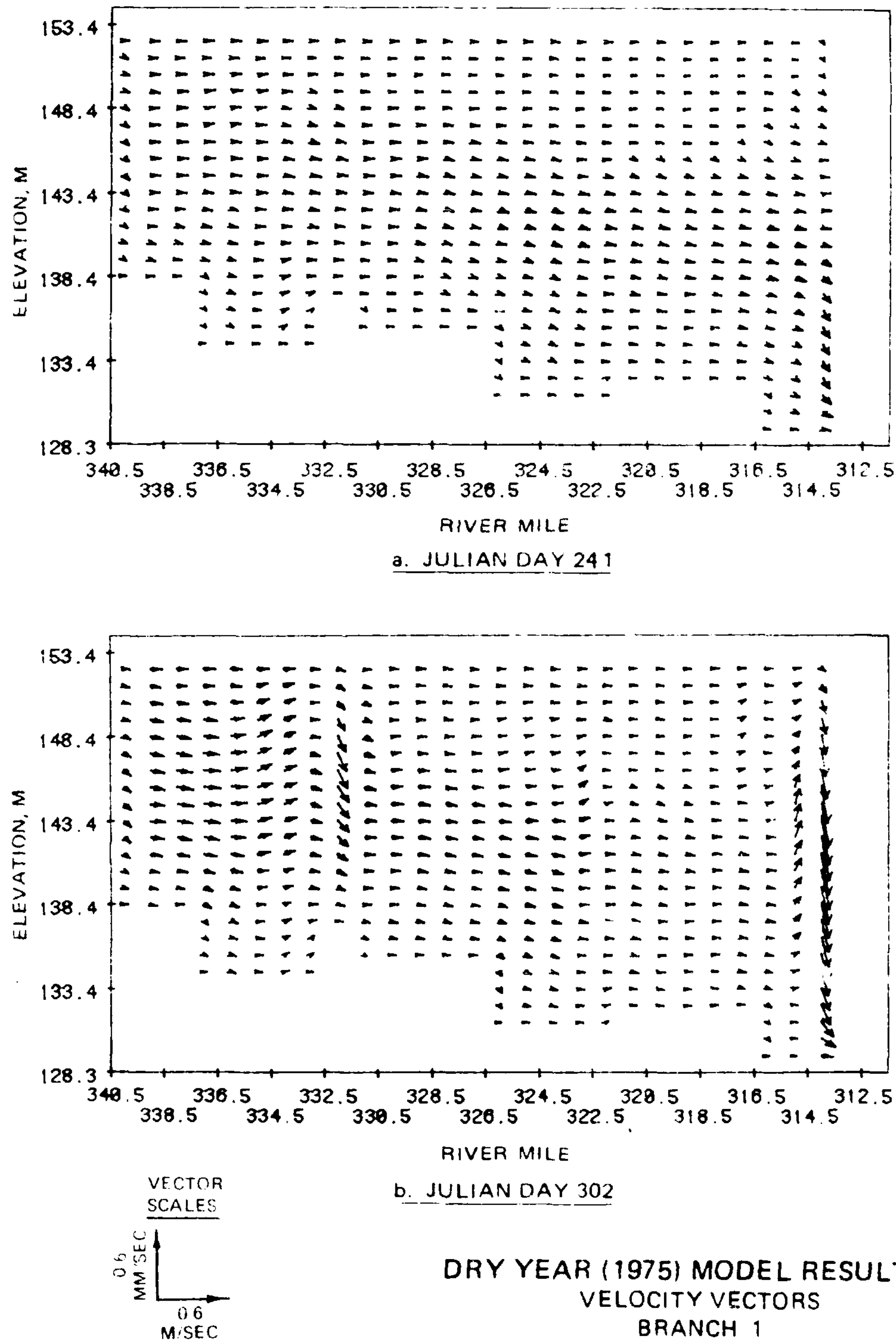
b. BRANCH 1

AVERAGE YEAR (1981) MODEL RESULTS
DO CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 302

PLATE 44

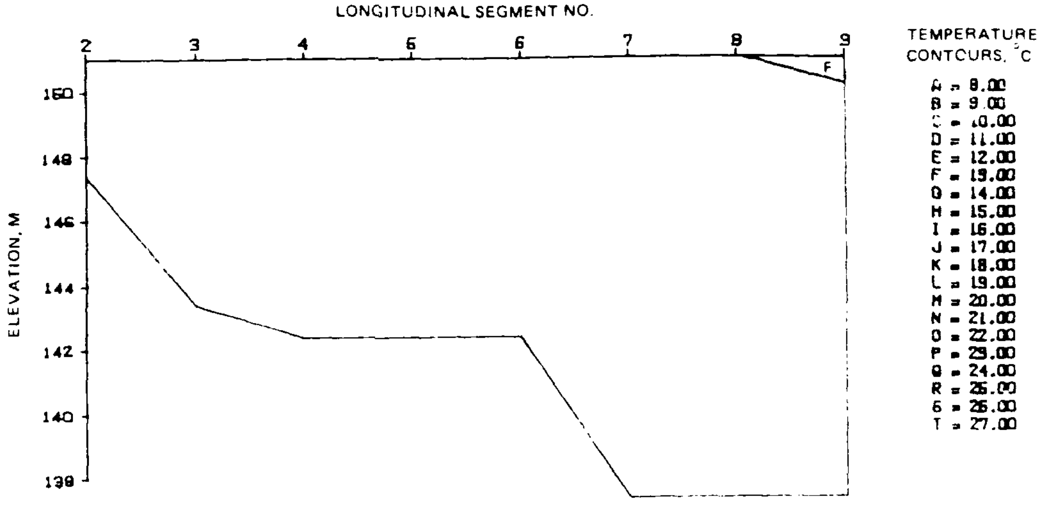


DRY YEAR (1975) MODEL RESULTS
VELOCITY VECTORS
BRANCH 1
JULIAN DAYS 119 AND 180

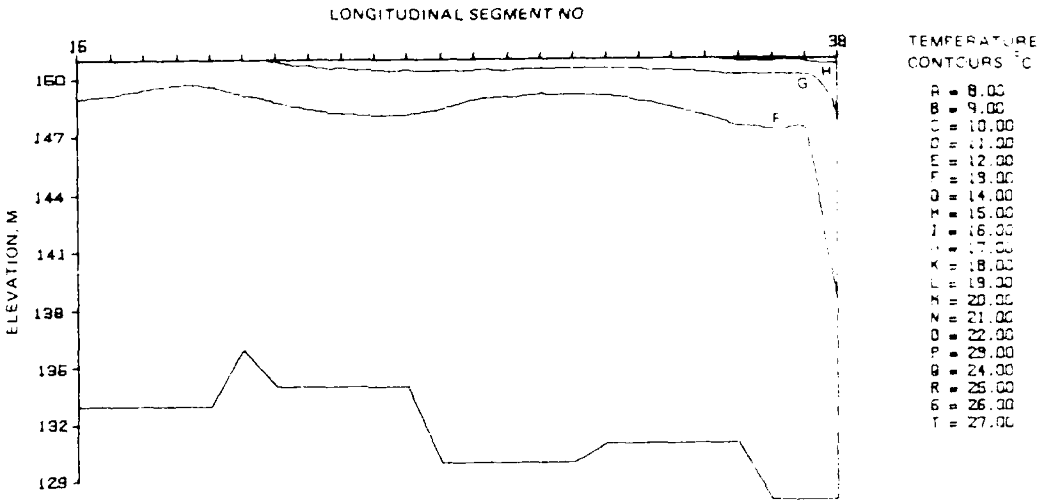


DRY YEAR (1975) MODEL RESULTS
VELOCITY VECTORS
BRANCH 1
JULIAN DAYS 241 AND 302

PLATE 46



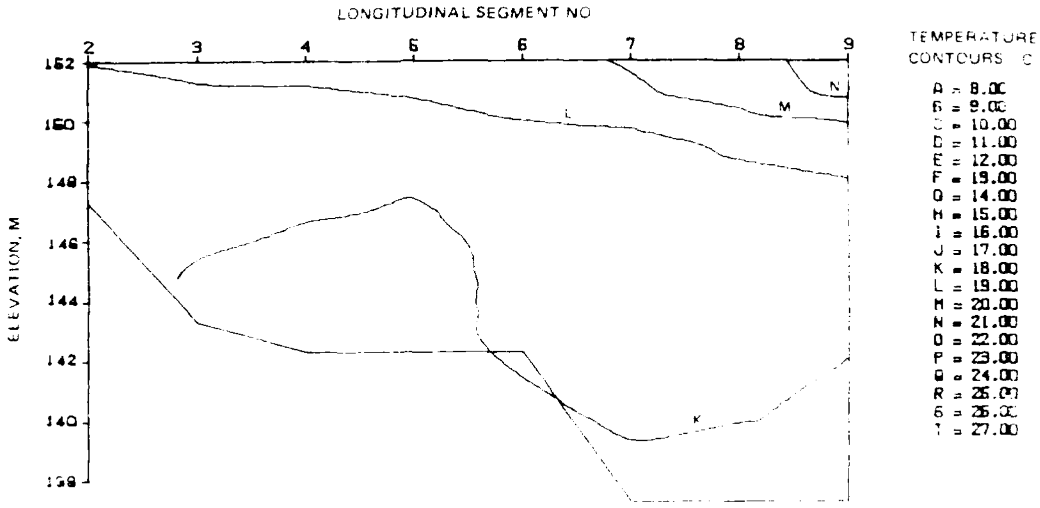
a. BRANCH 2



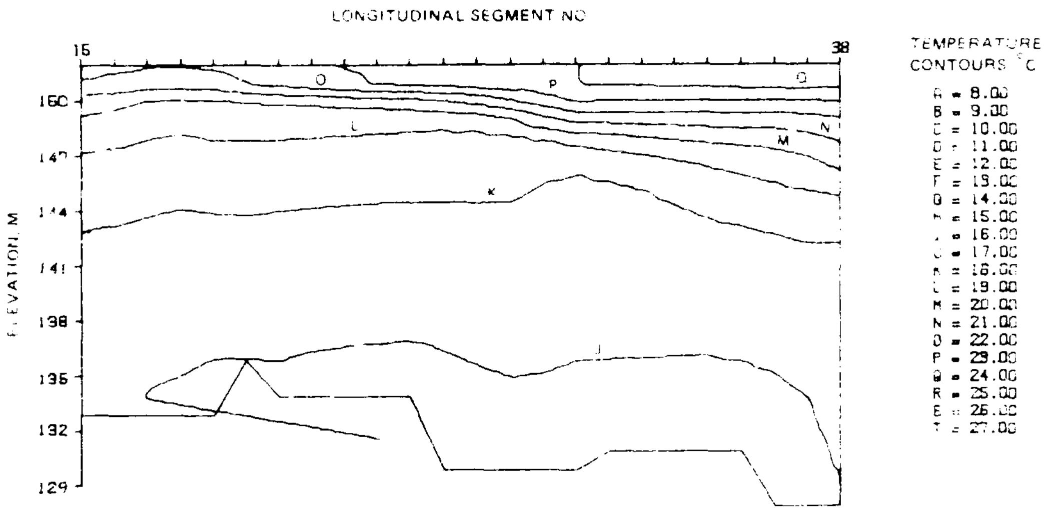
b. BRANCH 1

DRY YEAR (1975) MODEL RESULTS

TEMPERATURE CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 119



a. BRANCH 2

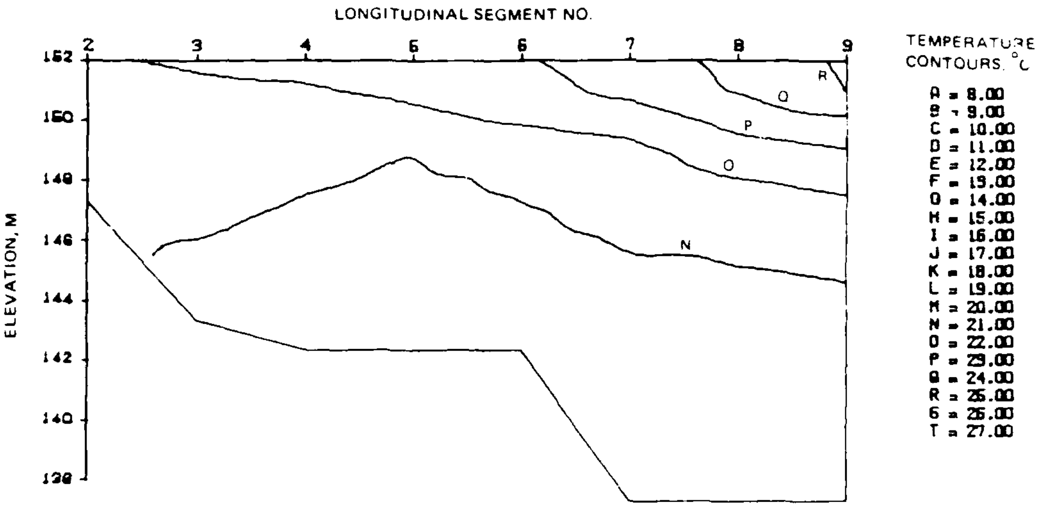


b. BRANCH 1

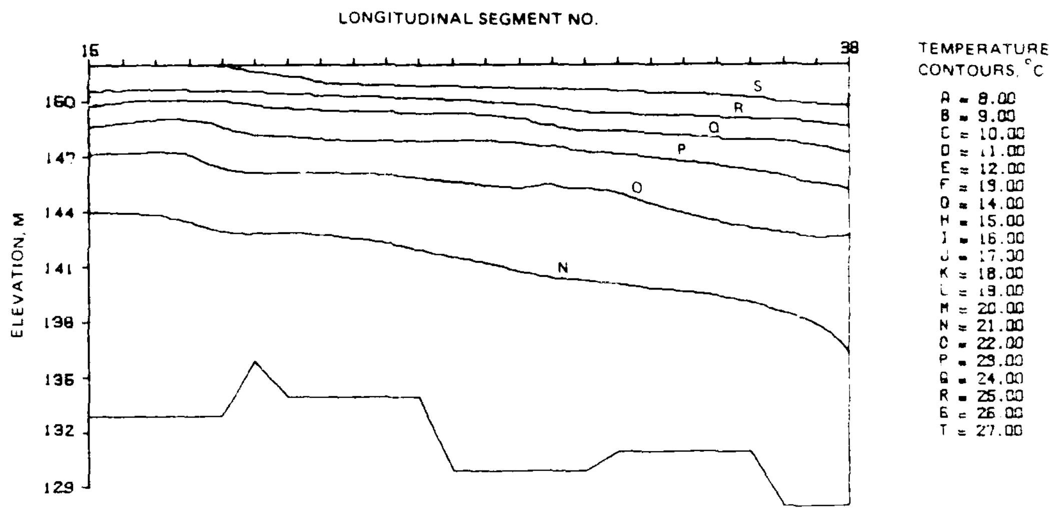
DRY YEAR (1975) MODEL RESULTS

TEMPERATURE CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 180

PLATE 48

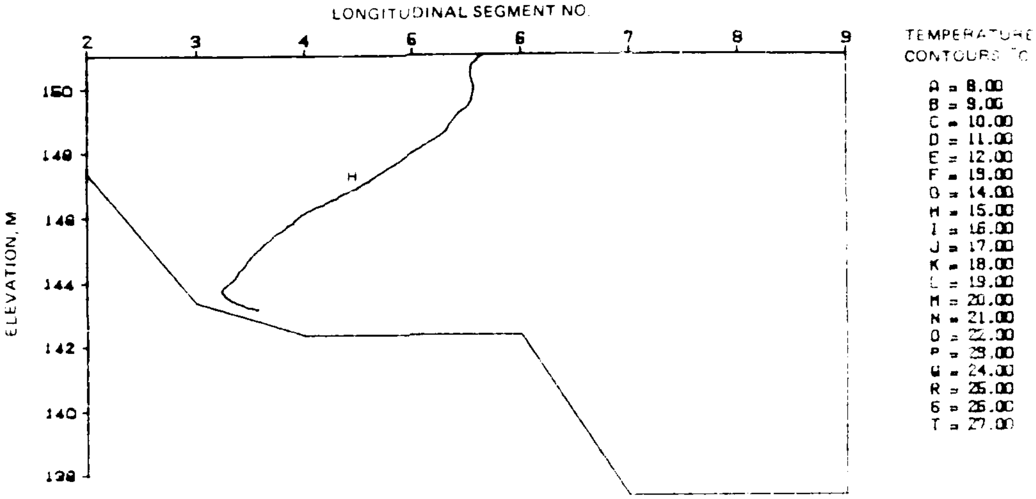


a. BRANCH 2

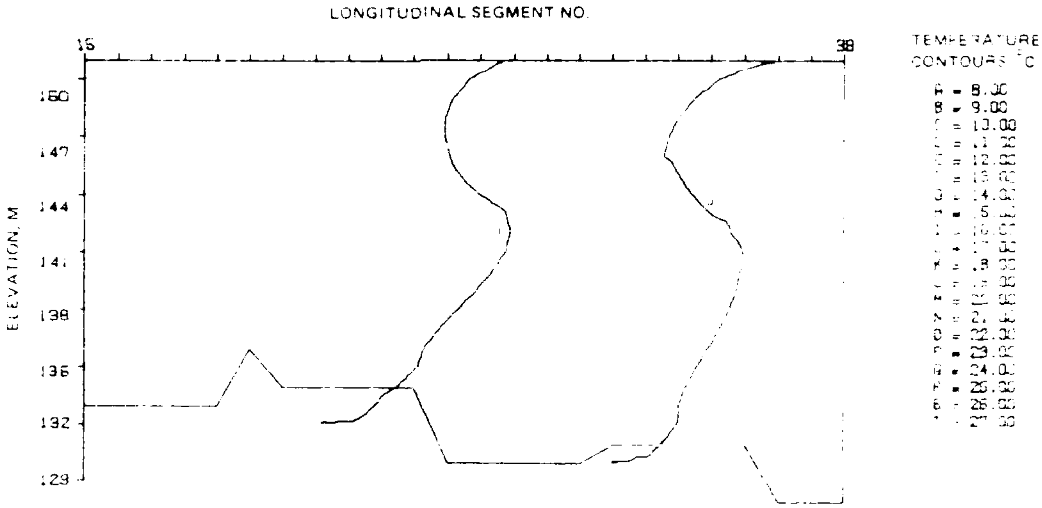


b. BRANCH 1

DRY YEAR (1975) MODEL RESULTS
TEMPERATURE CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 241



a. BRANCH 2



b. BRANCH 1

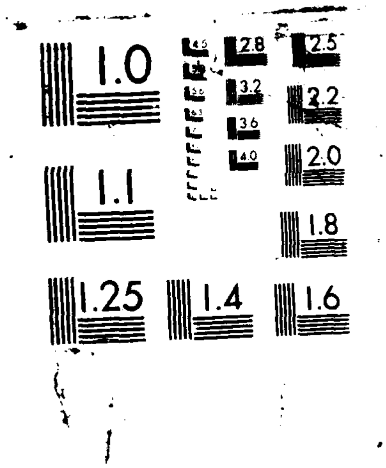
DRY YEAR (1975) MODEL RESULTS
TEMPERATURE CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 302

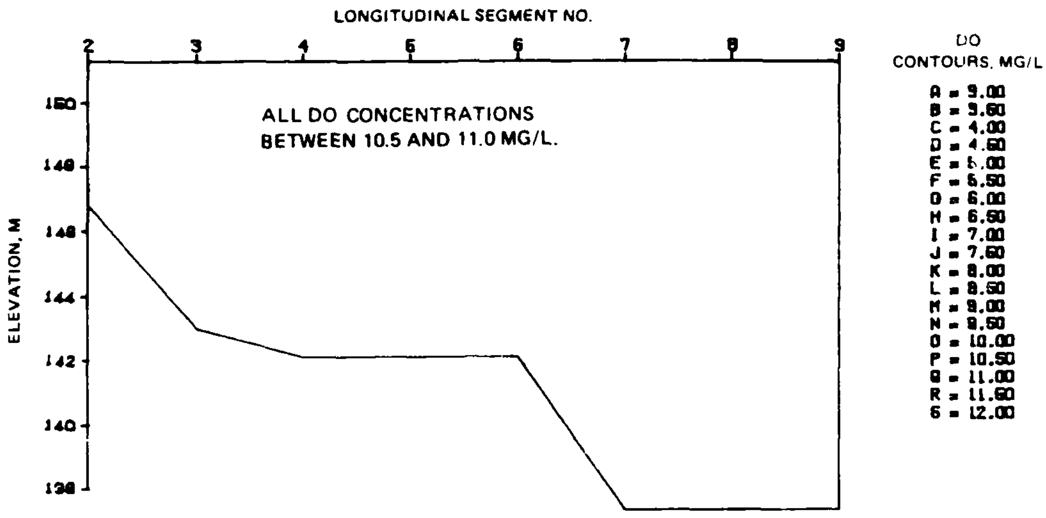
PLATE 50

AD-A198 899 APPLICATION OF A TWO-DIMENSIONAL MODEL OF HYDRODYNAMICS AND WATER QUALITY..(U) ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MS HYDRA.. S E HOWINGTON 2/2

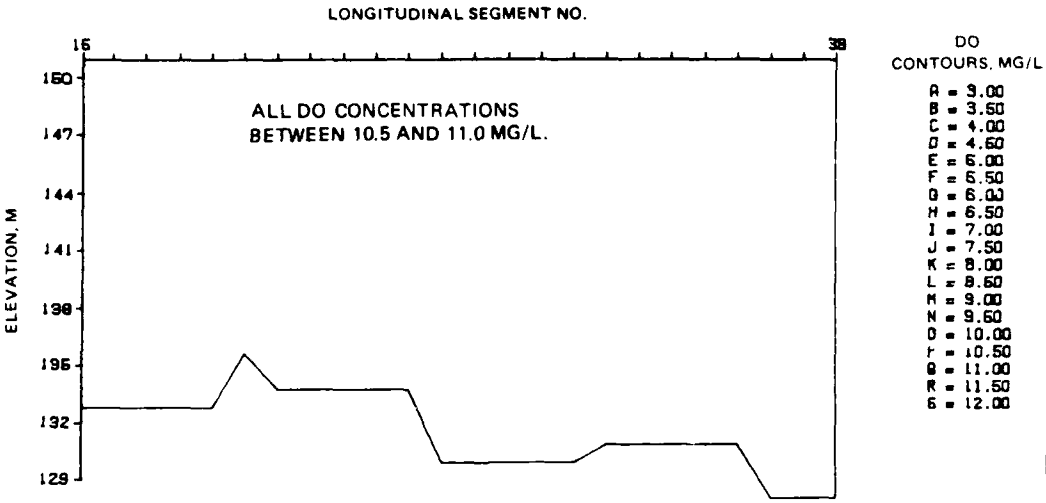
UNCLASSIFIED AUG 88 WES/TR/HL-88-19 F/G 13/2 NL

END
DATE
FILMED
10 88


1.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6

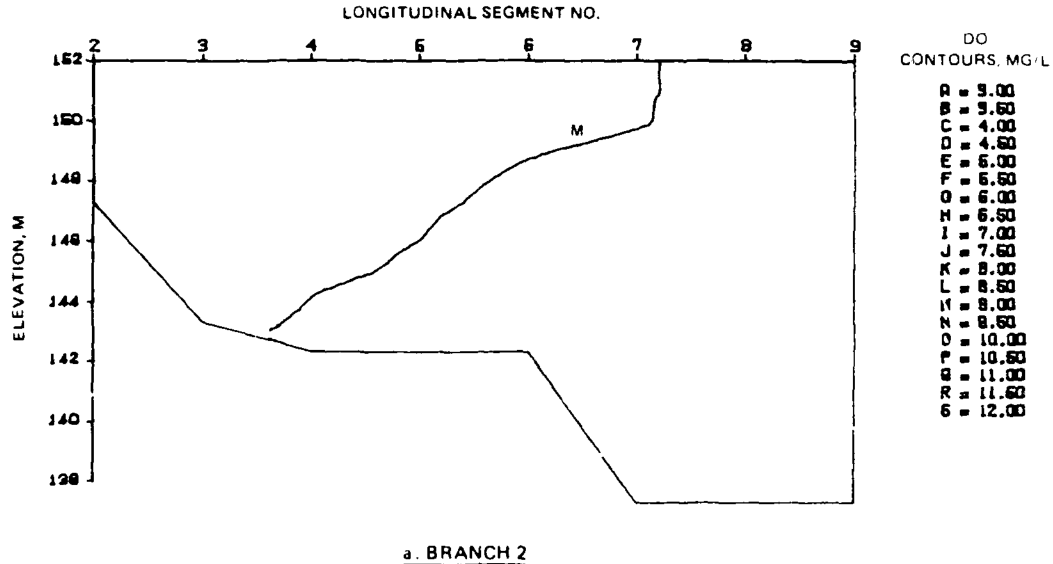


a. BRANCH 2

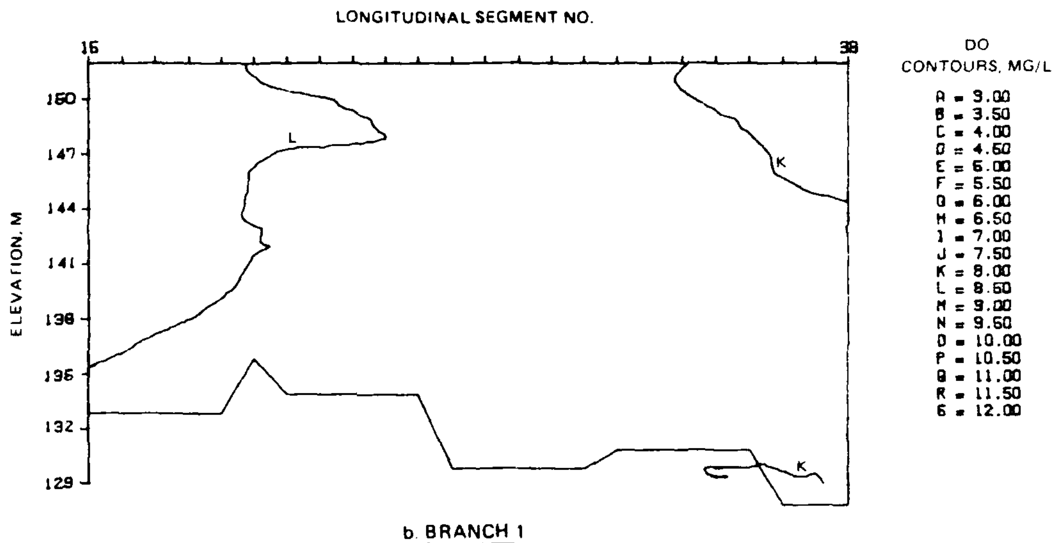


b. BRANCH 1

DRY YEAR(1975) MODEL RESULTS
DO CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 119



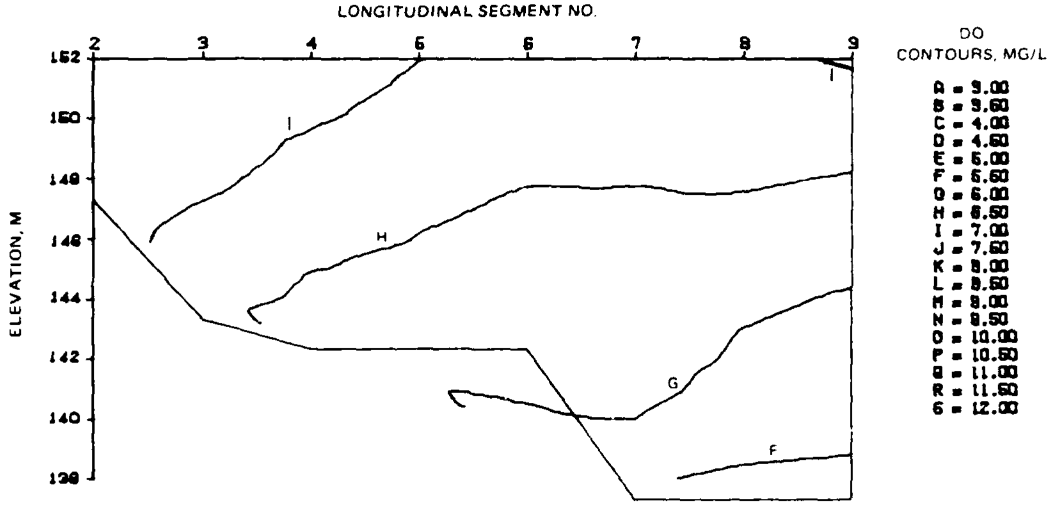
a. BRANCH 2



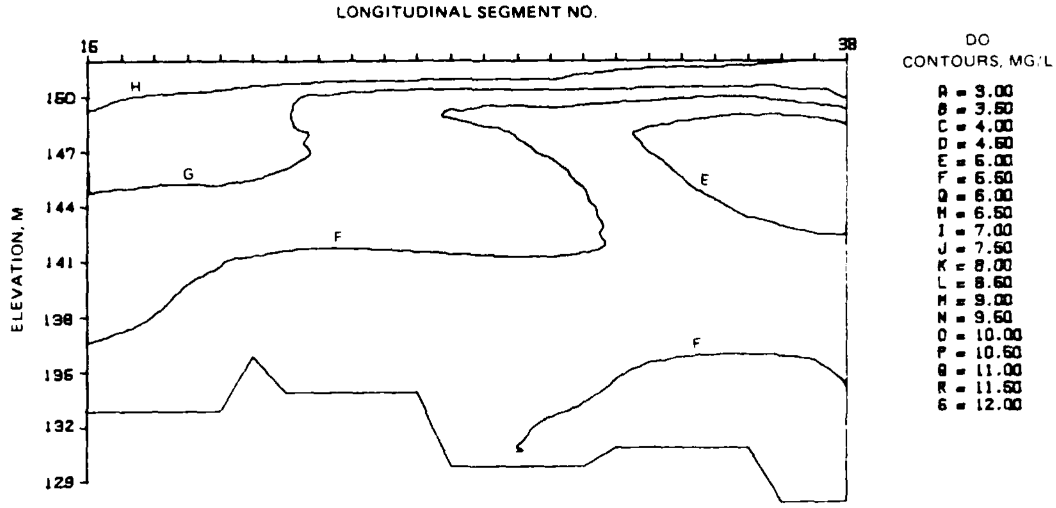
b. BRANCH 1

DRY YEAR(1975) MODEL RESULTS
DO CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 180

PLATE 52

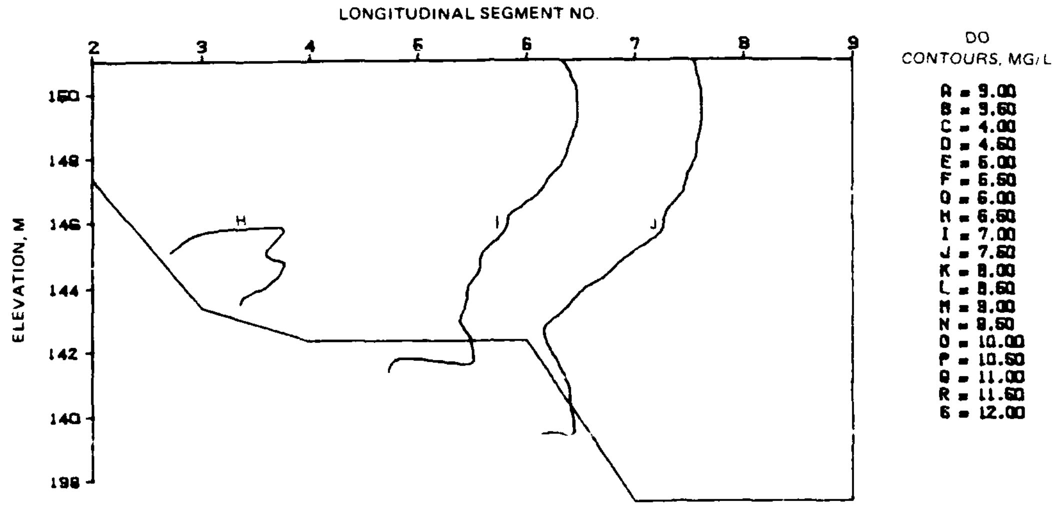


a. BRANCH 2

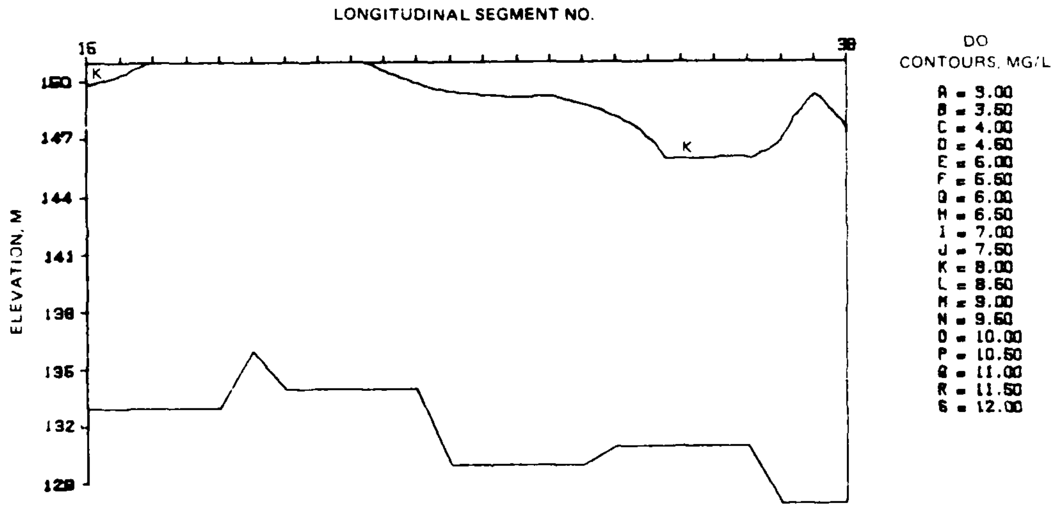


b. BRANCH 1

DRY YEAR (1975) MODEL RESULTS
DO CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 241

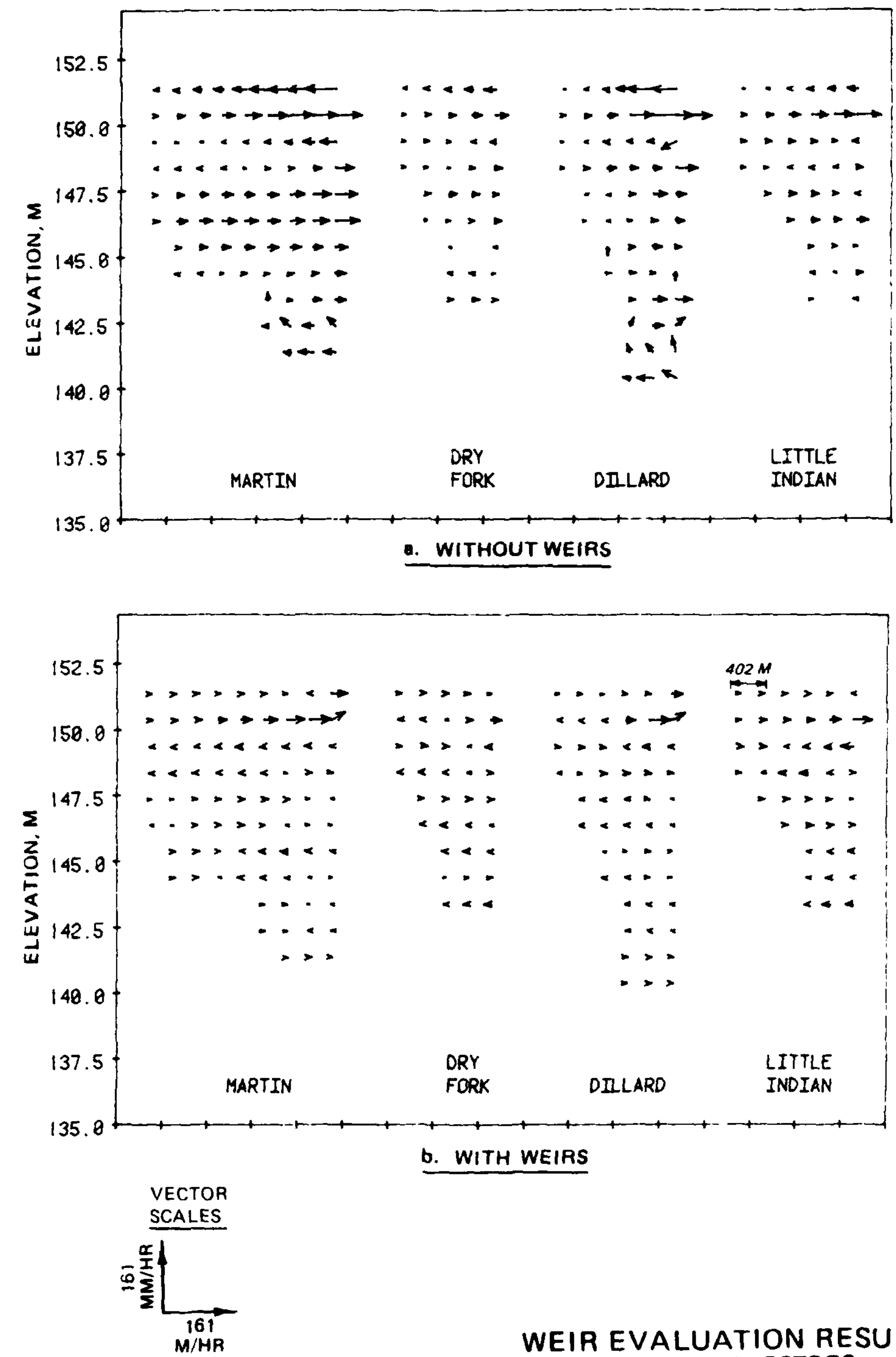


a. BRANCH 2

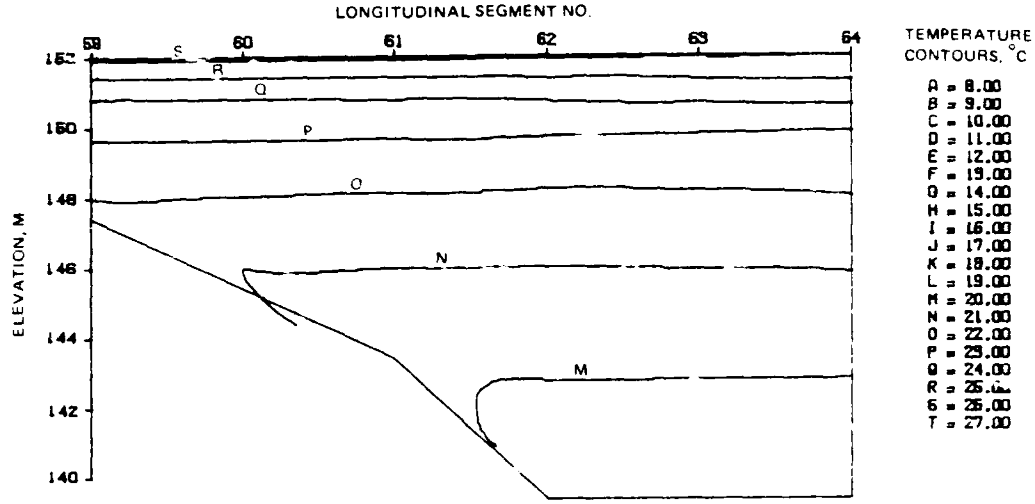


b. BRANCH 1

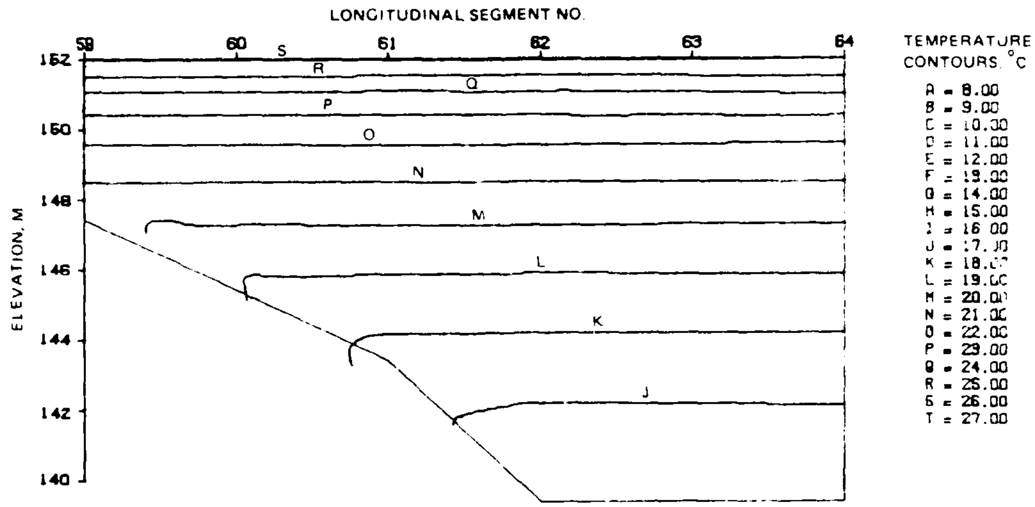
DRY YEAR(1975) MODEL RESULTS
DO CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 302



WEIR EVALUATION RESULTS
VELOCITY VECTORS
JULIAN DAY 210

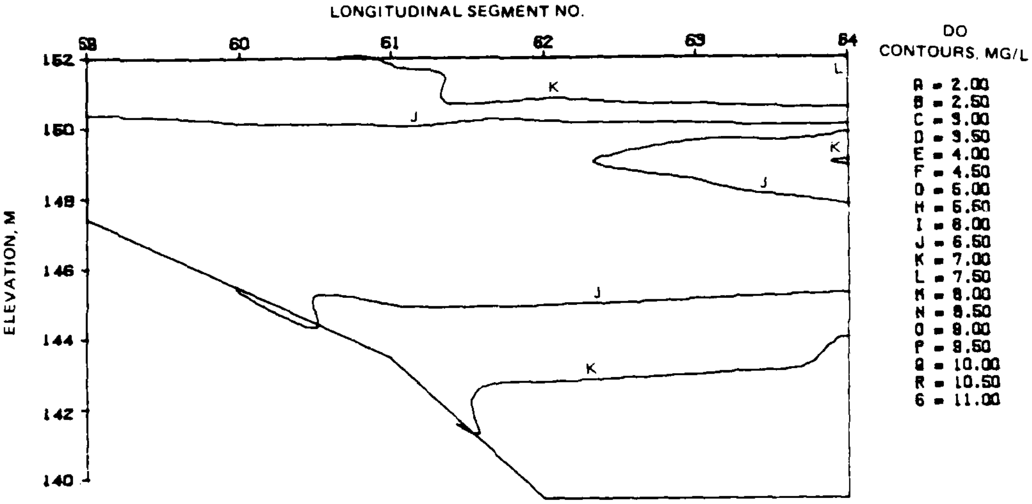


a. WITHOUT WEIRS

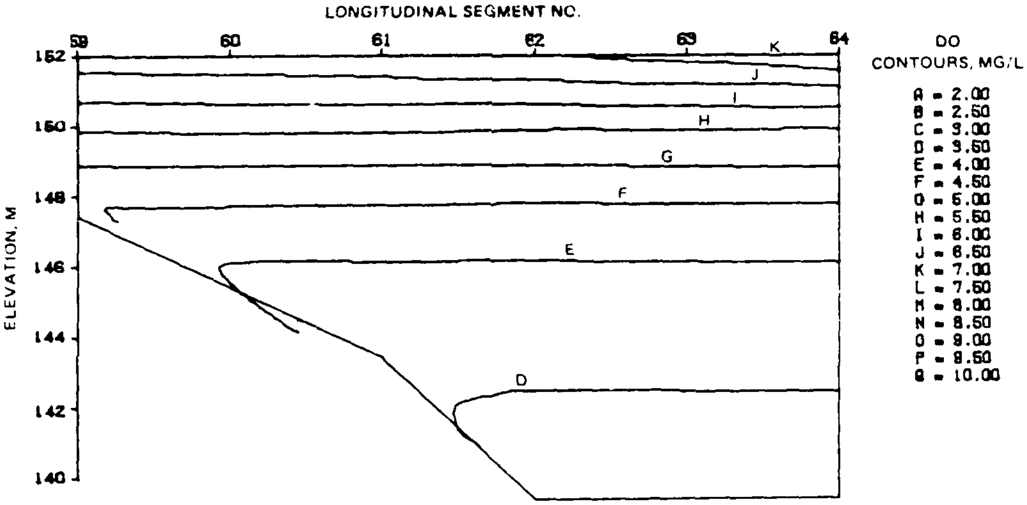


b. WITH WEIRS

WEIR EVALUATION RESULTS
TEMPERATURE CONTOURS
BRANCH 5
JULIAN DAY 210



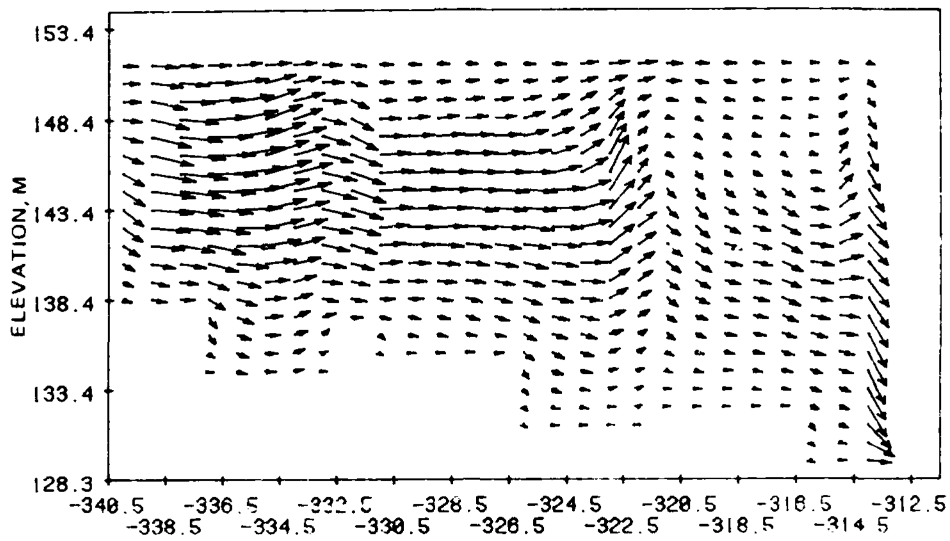
a. WITHOUT WEIRS



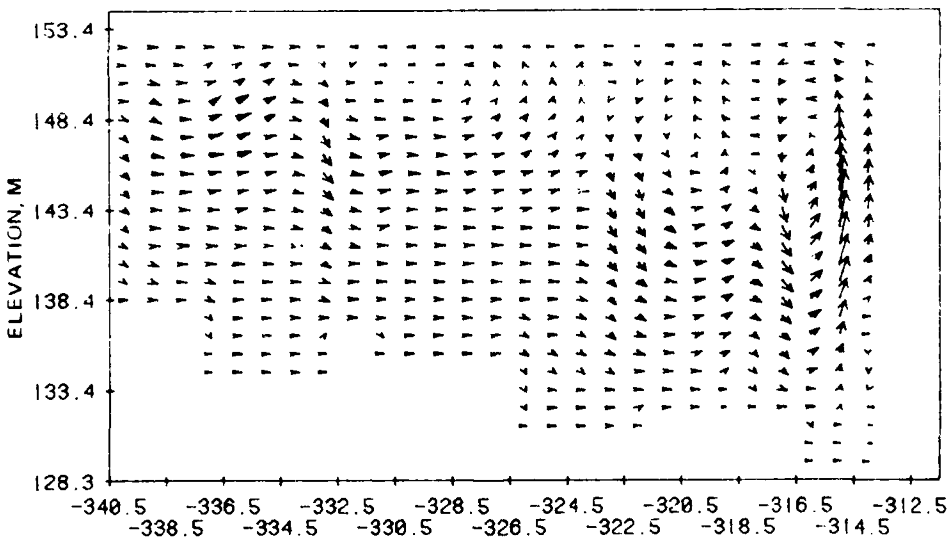
b. WITH WEIRS

WEIR EVALUATION RESULTS

DO CONTOURS
BRANCH 5
JULIAN DAY 210

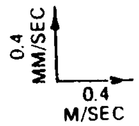


a DURING OPERATION (JULIAN DAY 219)

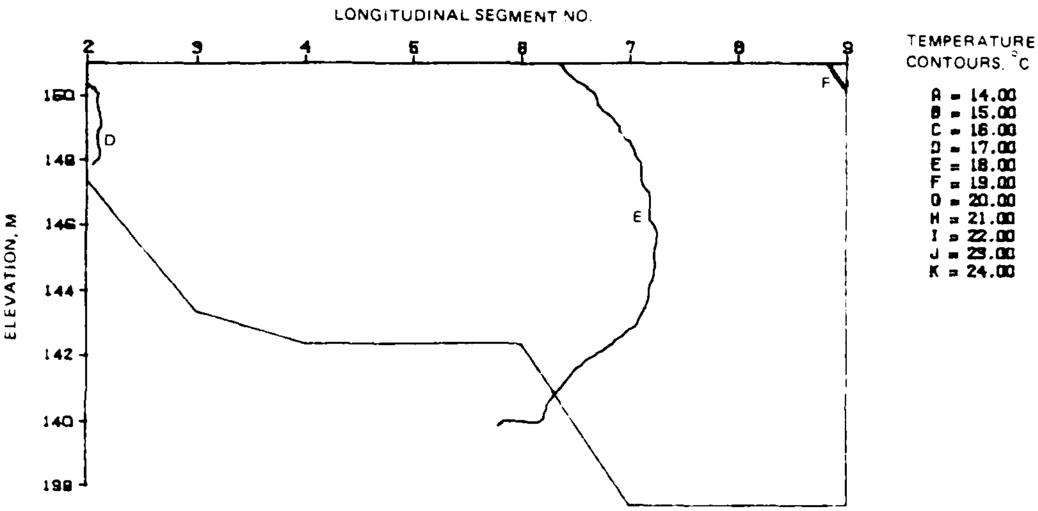


b. NOT OPERATING (JULIAN DAY 222)

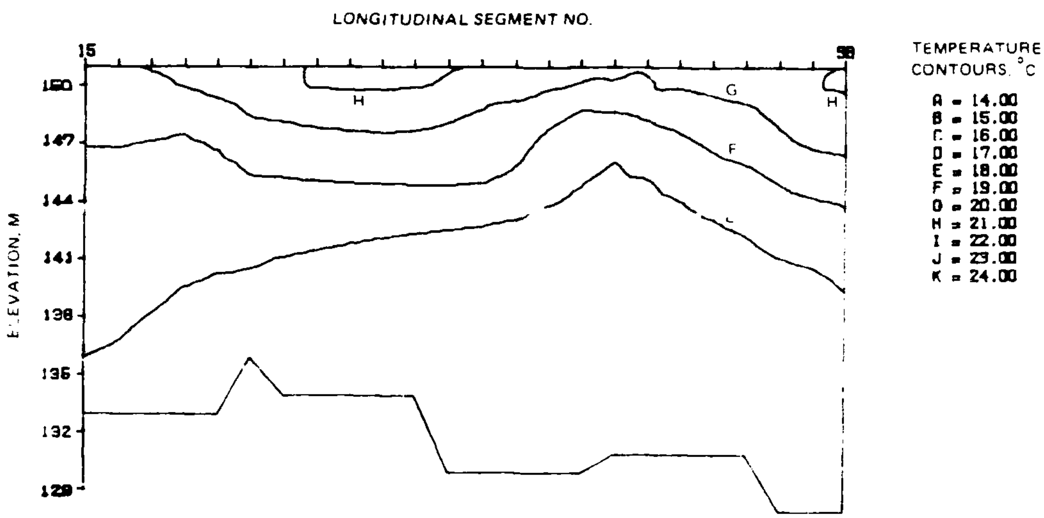
VECTOR SCALES



HYDROPOWER OPERATION RESULTS
VELOCITY VECTORS
BRANCH 1
JULIAN DAYS 219 AND 222

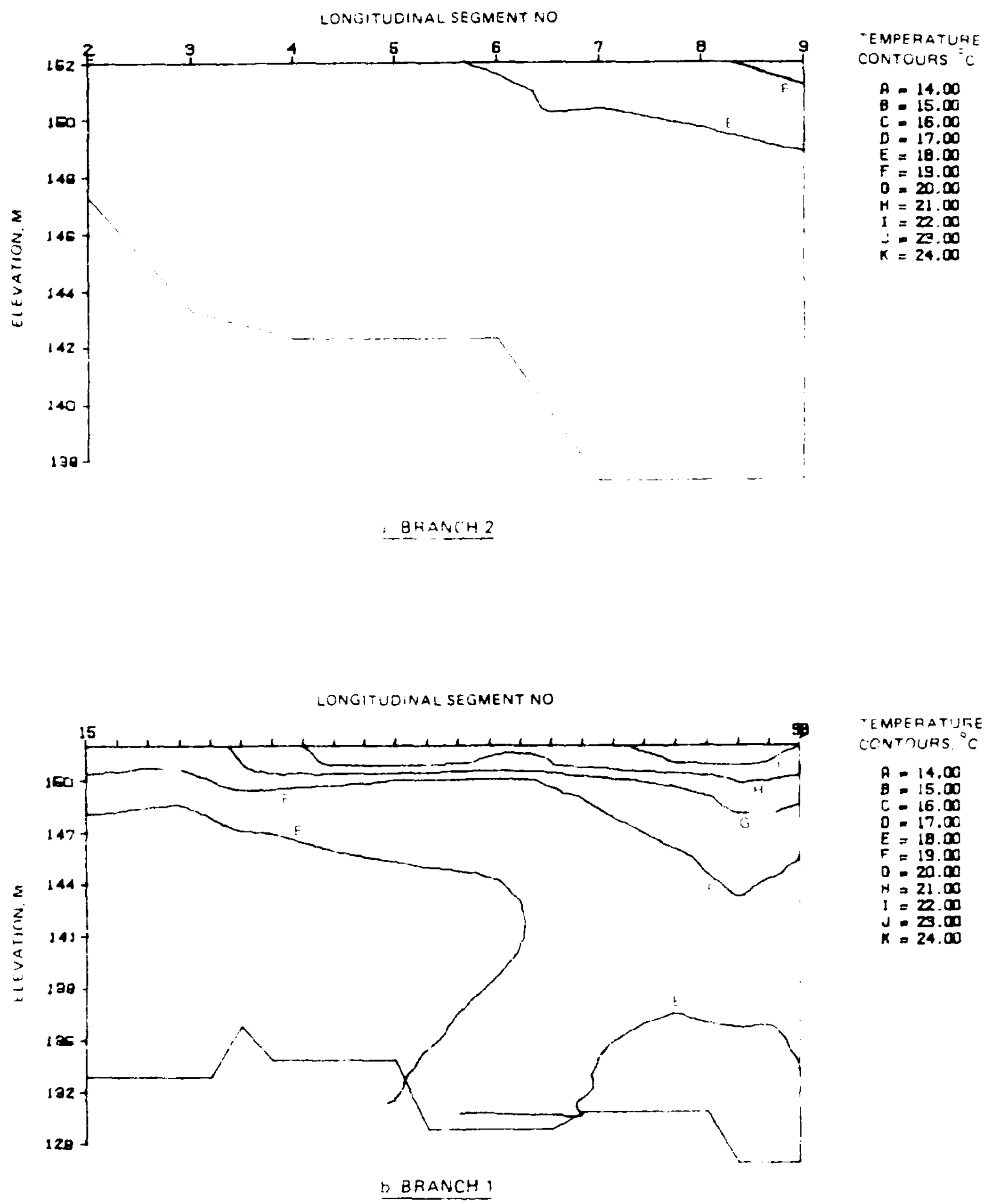


a. BRANCH 2

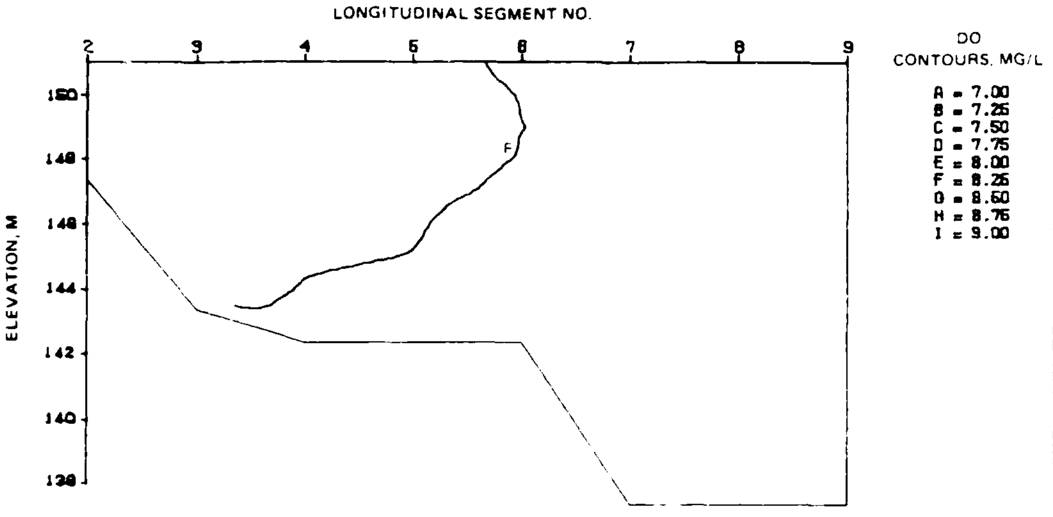


b. BRANCH 1

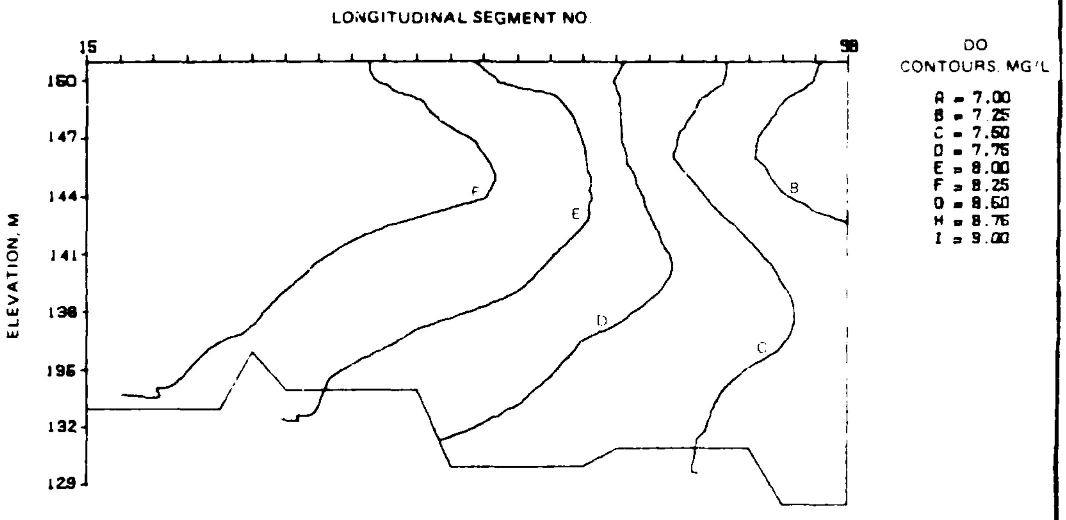
HYDROPOWER OPERATION RESULTS
TEMPERATURE CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 219



HYDROPOWER OPERATION RESULTS
TEMPERATURE CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 222



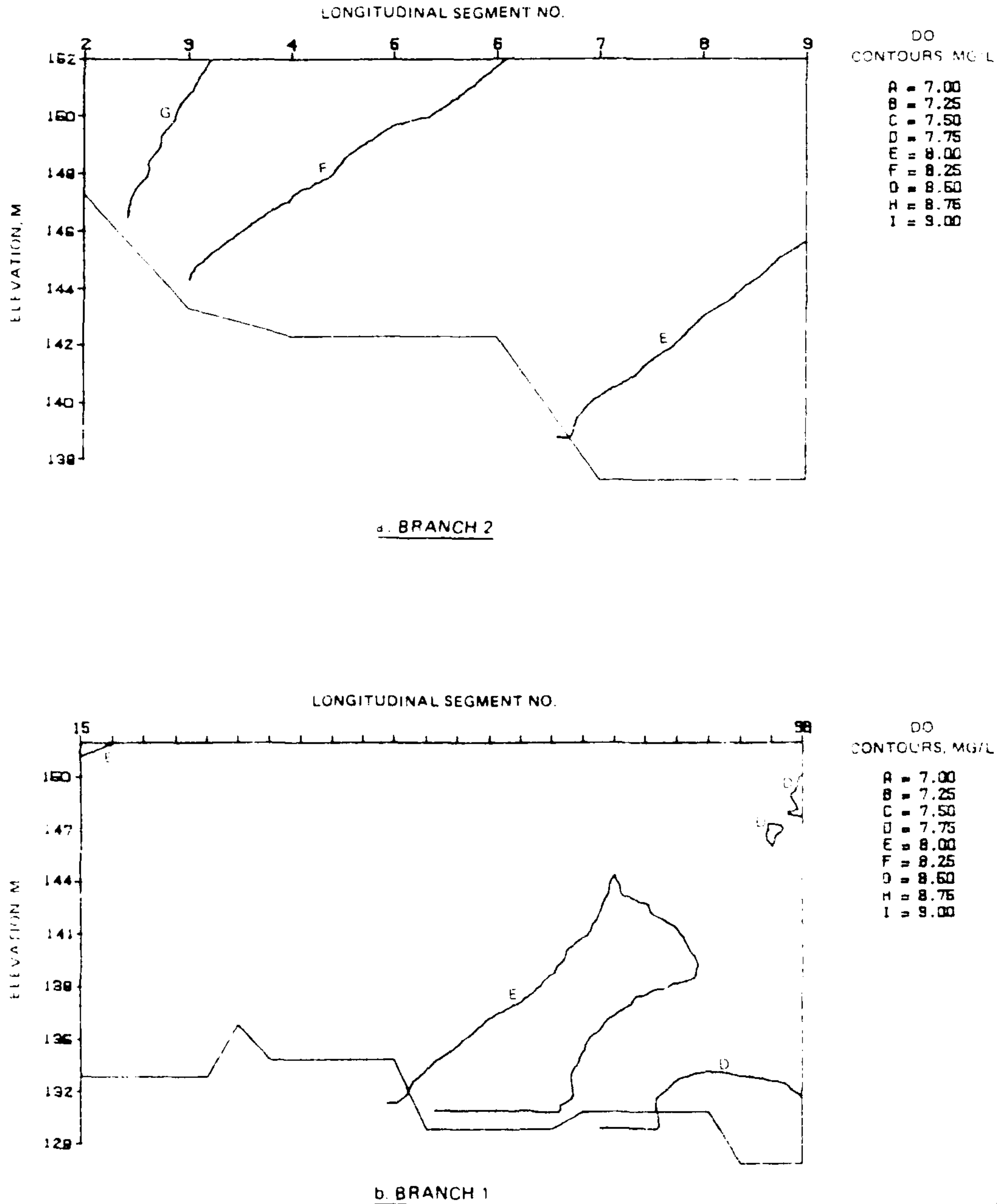
a. BRANCH 2



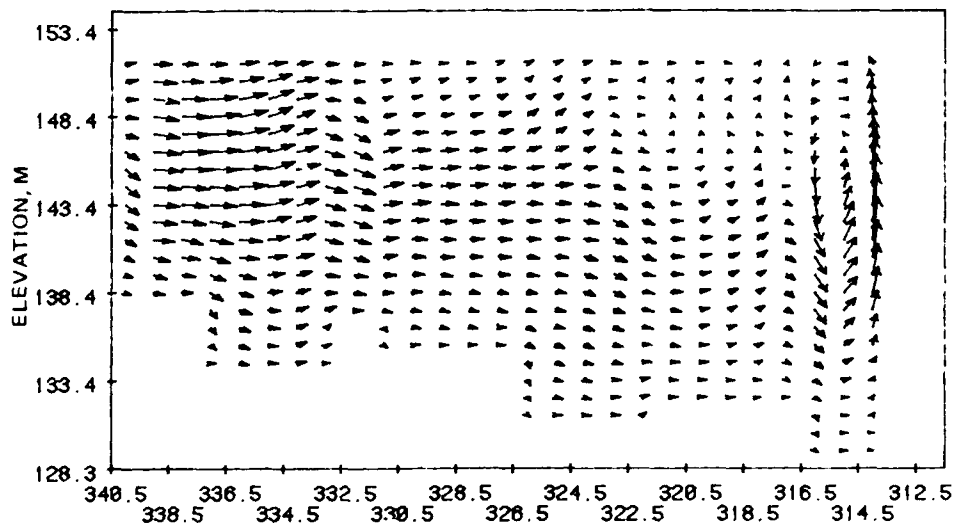
b. BRANCH 1

HYDROPOWER OPERATION RESULTS
DO CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 219

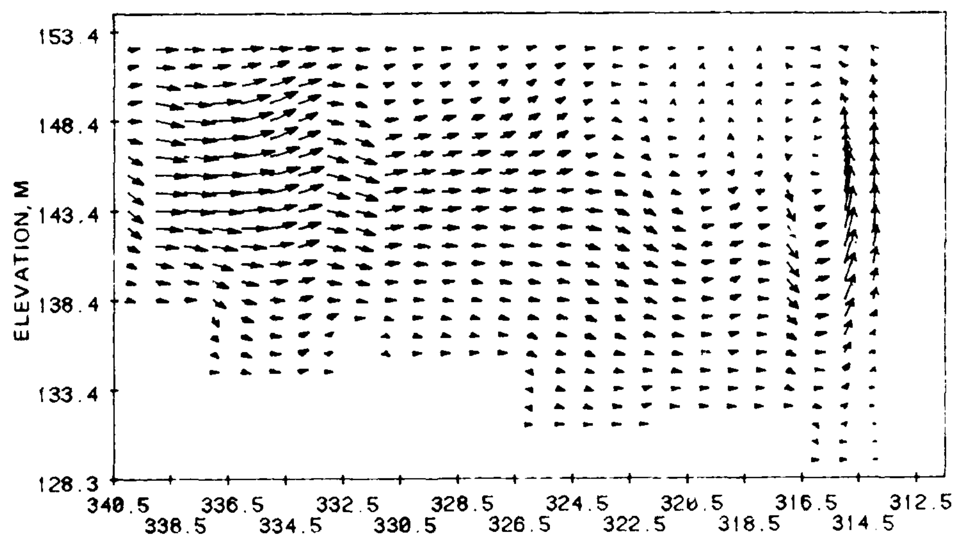
PLATE 61



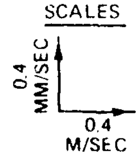
HYDROPOWER OPERATION RESULTS
DO CONTOURS
BRANCHES 1 AND 2
JULIAN DAY 222



a. JULIAN DAY 214.12

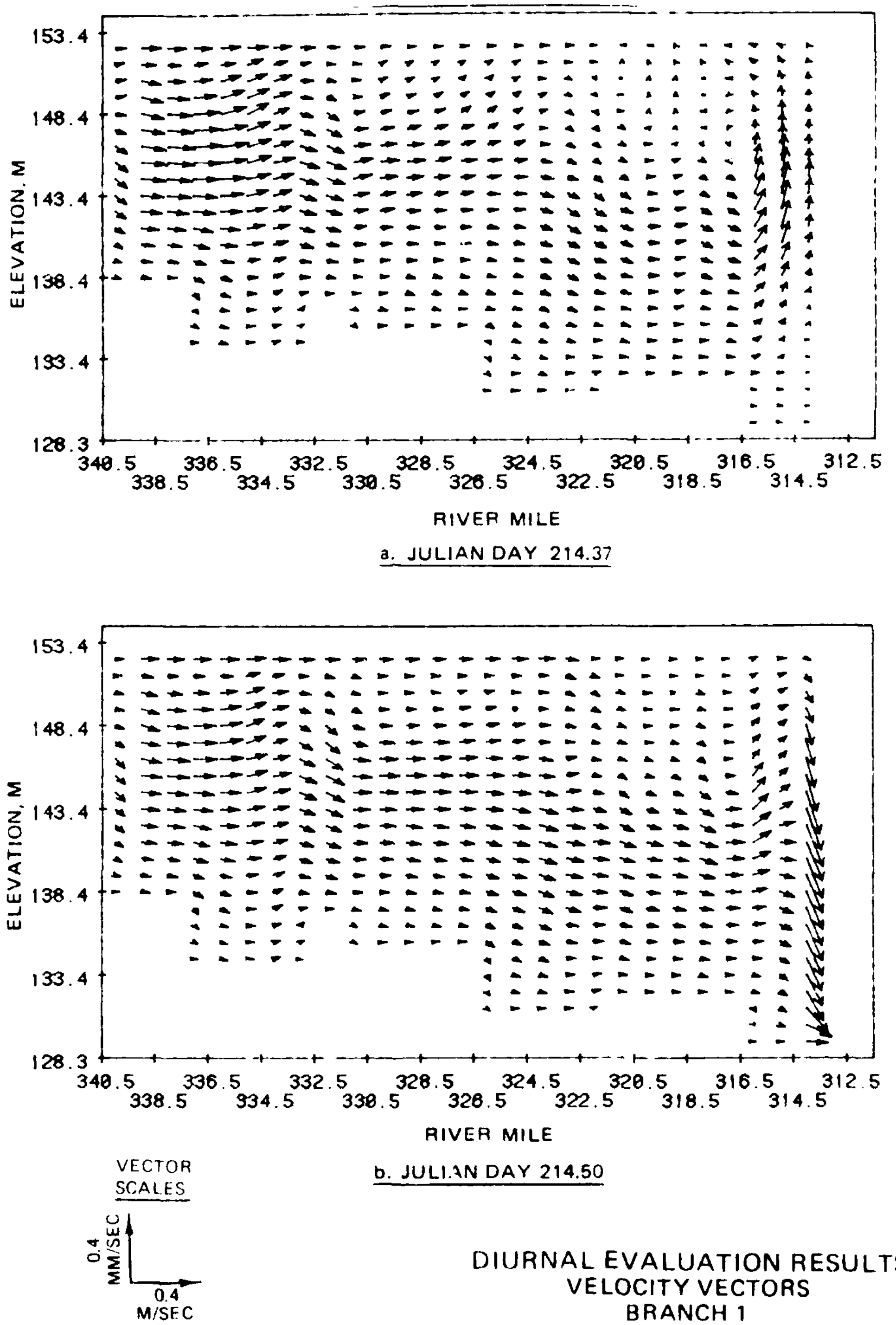


VECTOR SCALES

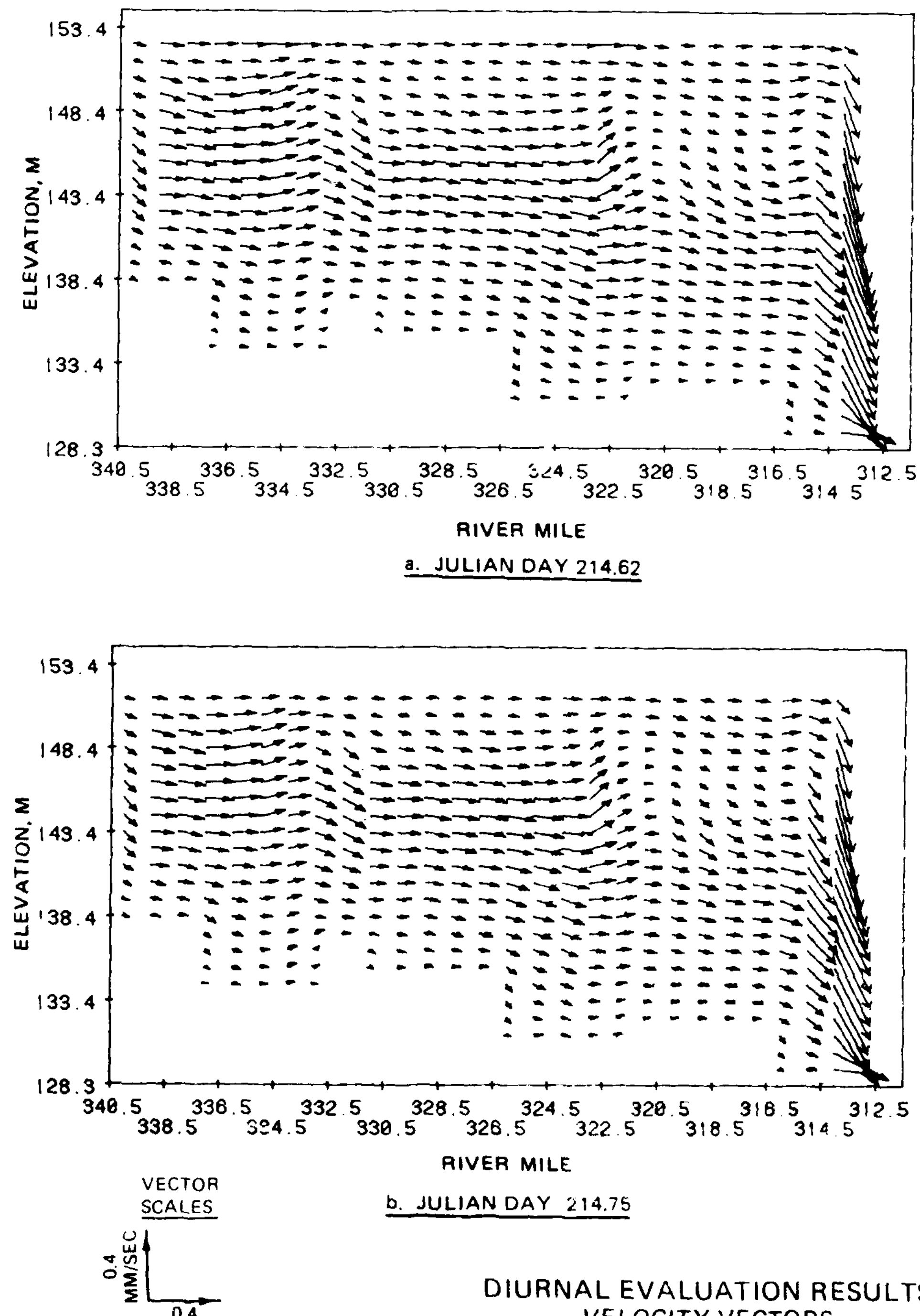


b. JULIAN DAY 214.25

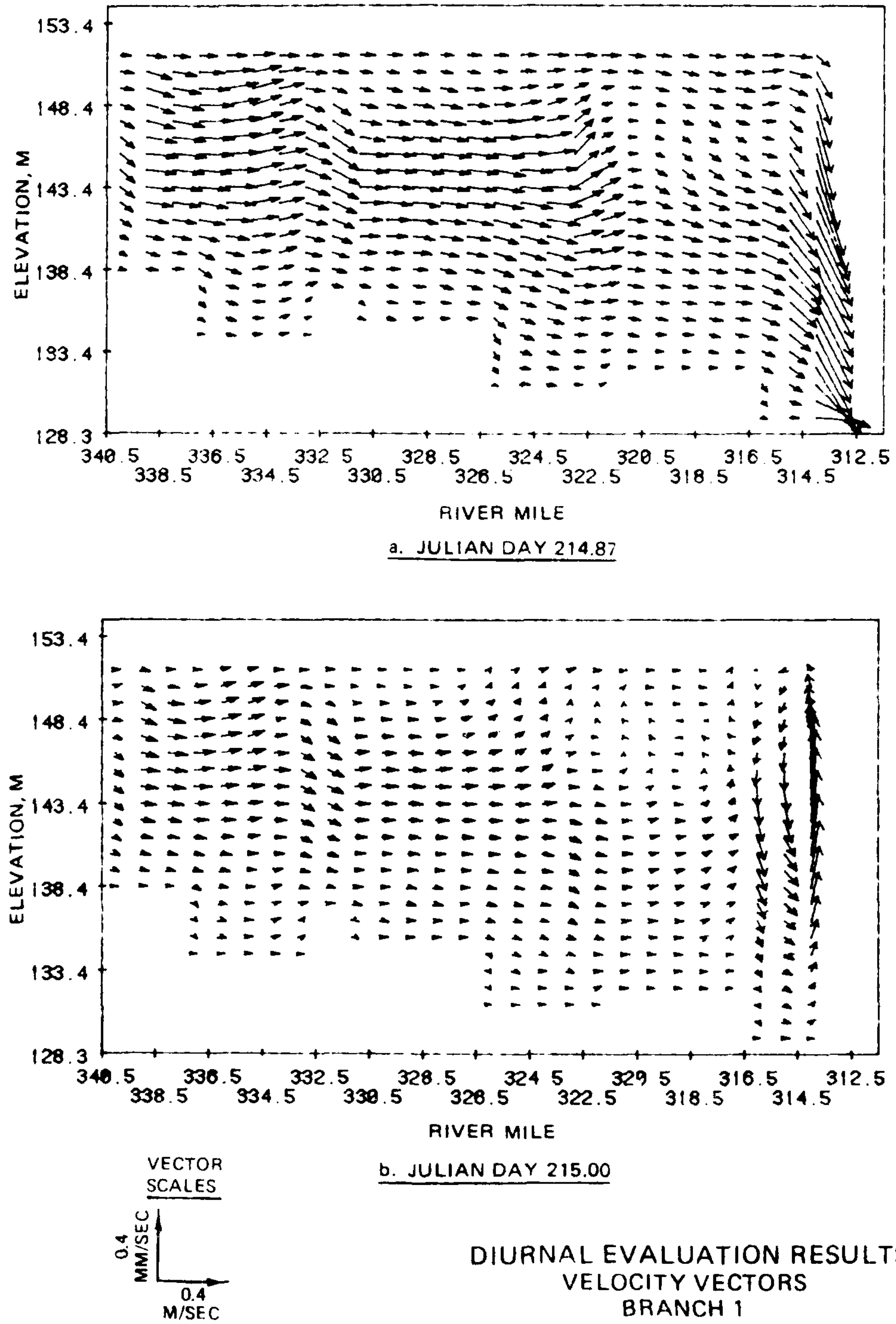
DIURNAL EVALUATION RESULTS
VELOCITY VECTORS
BRANCH 1
JULIAN DAYS 214.12 AND 214.25



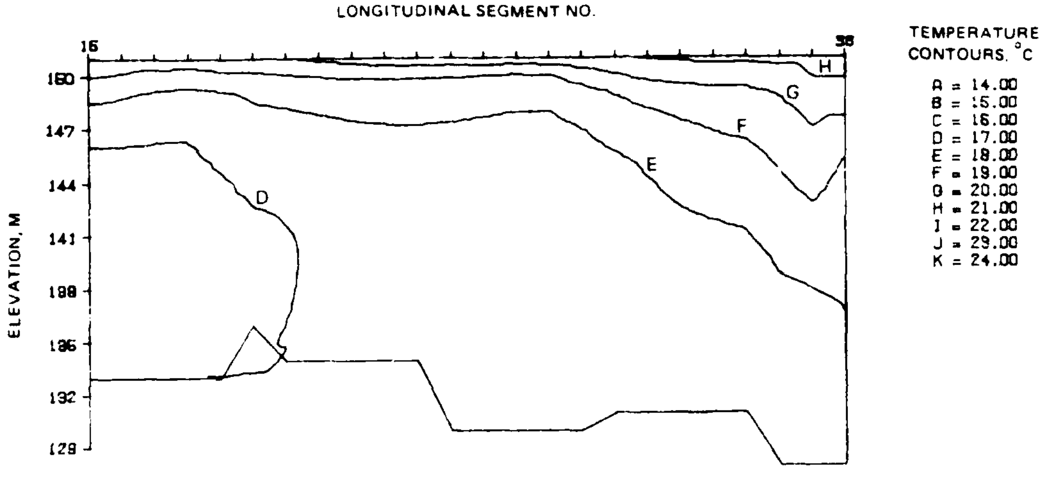
DIURNAL EVALUATION RESULTS
VELOCITY VECTORS
BRANCH 1
JULIAN DAYS 214.37 AND 214.50



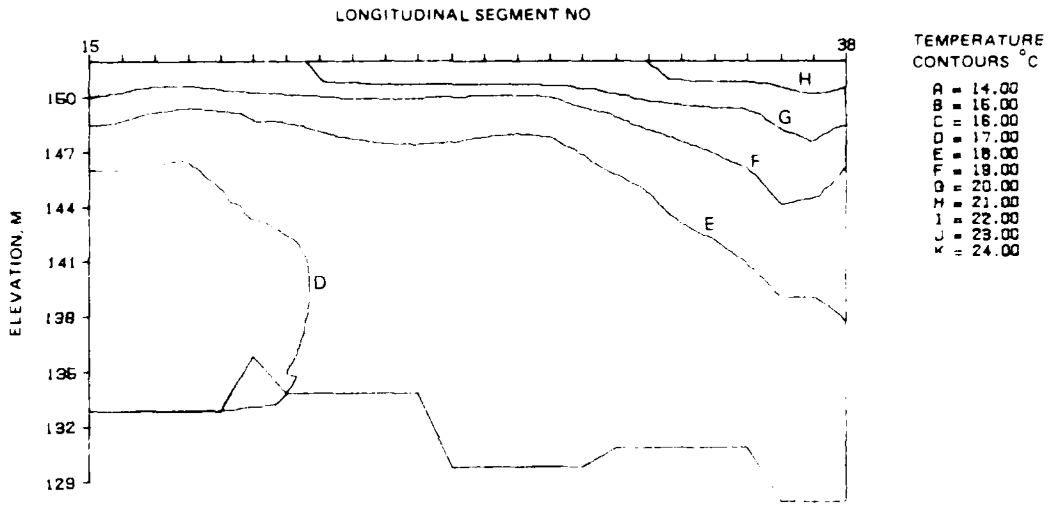
DIURNAL EVALUATION RESULTS
VELOCITY VECTORS
BRANCH 1
JULIAN DAYS 214.62 AND 214.75



DIURNAL EVALUATION RESULTS
VELOCITY VECTORS
BRANCH 1
JULIAN DAYS 214.87 AND 215.00

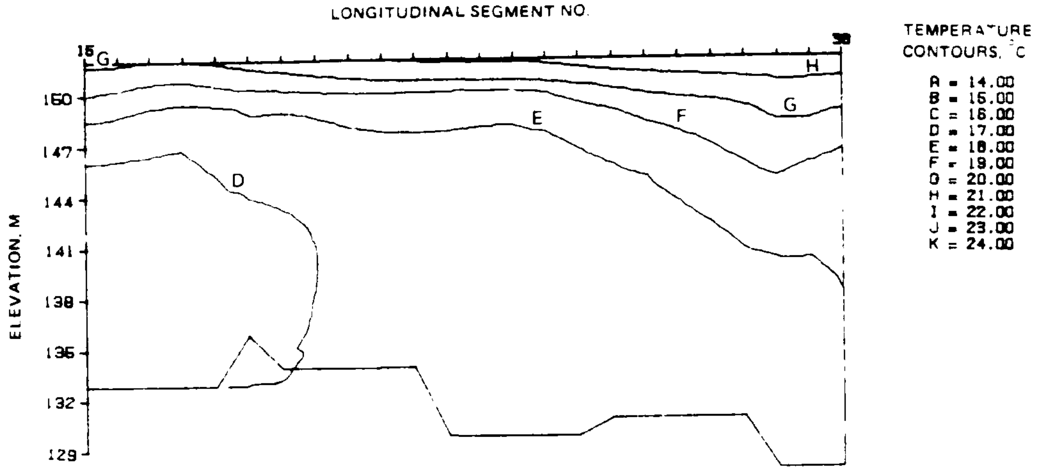


a. JULIAN DAY 214.12



b. JULIAN DAY 214.25

DIURNAL EVALUATION RESULTS
TEMPERATURE CONTOURS
BRANCH 1
JULIAN DAYS 214.12 AND 214.25



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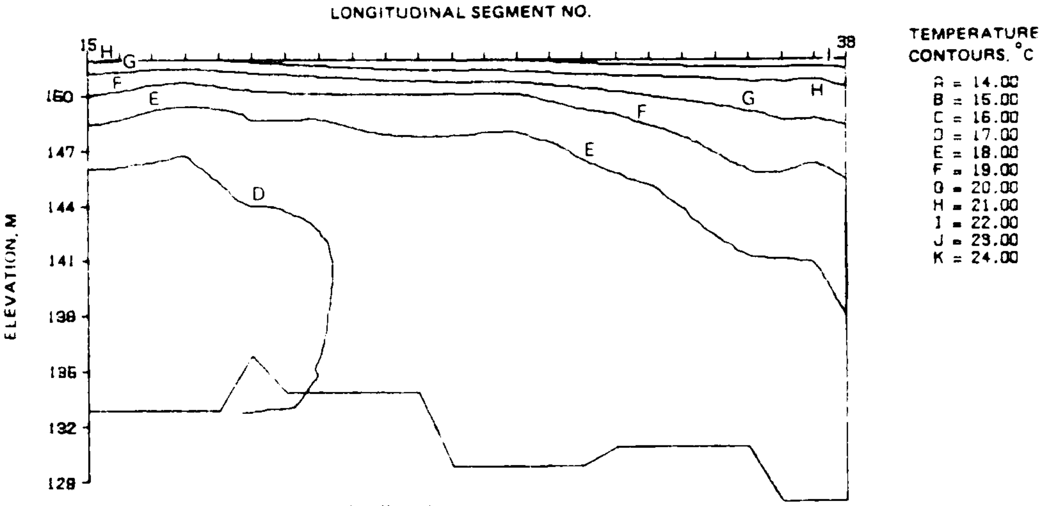
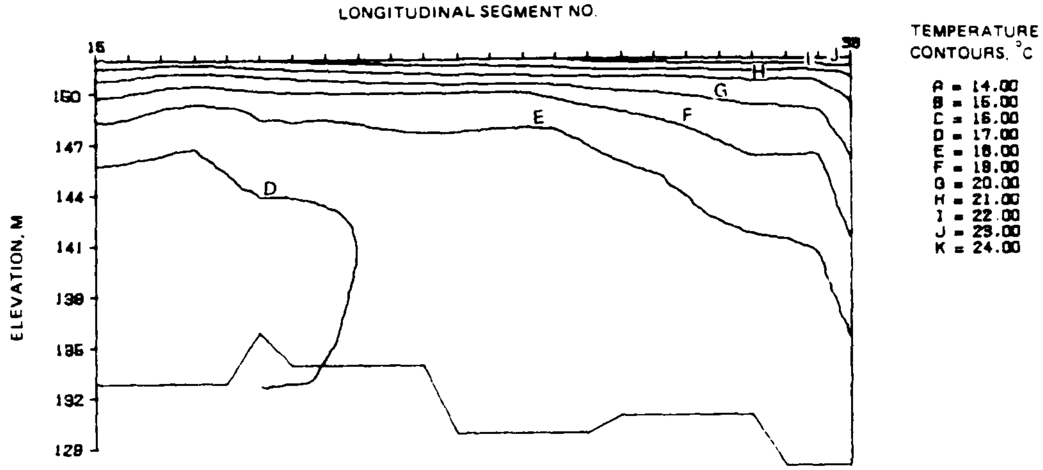


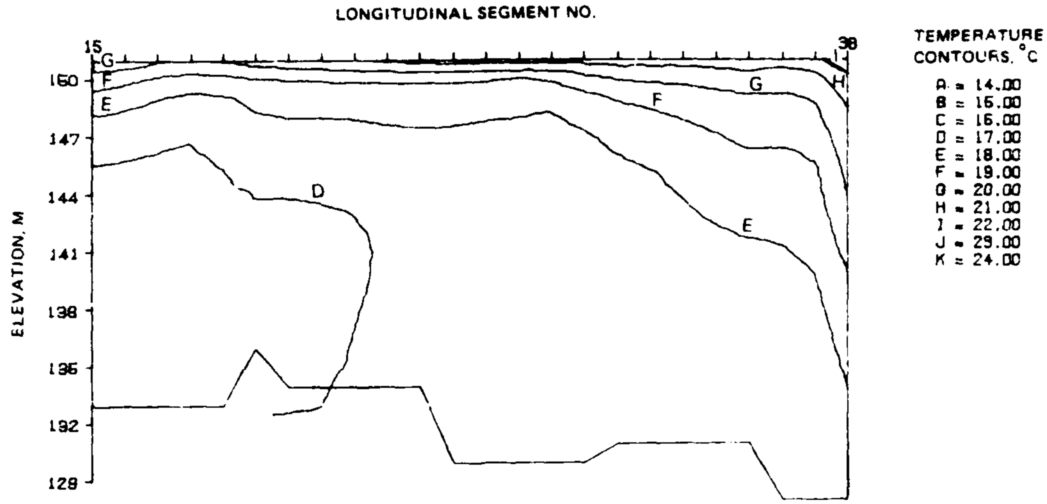
b. JULIAN DAY 214.50

DIURNAL EVALUATION RESULTS
TEMPERATURE CONTOURS
BRANCH 1
JULIAN DAYS 214.37 AND 214.50

PLATE 68

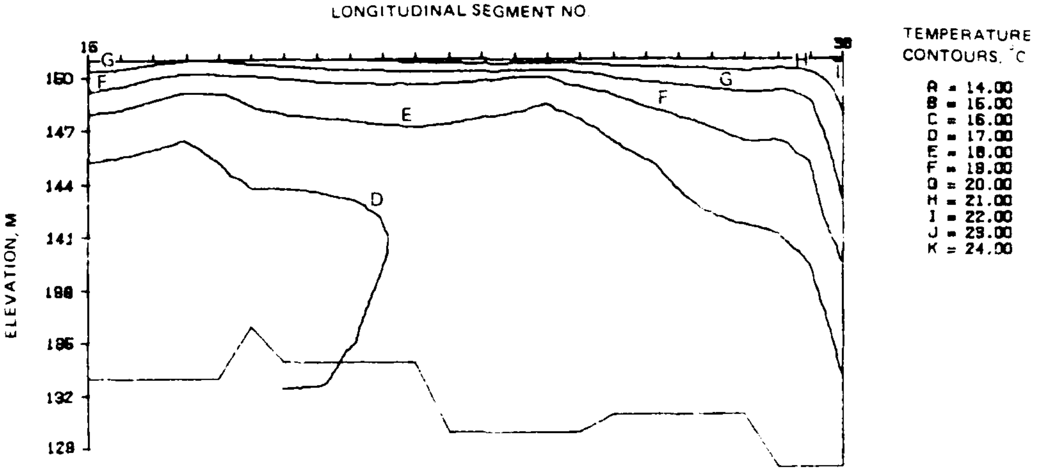


a. JULIAN DAY 214.62

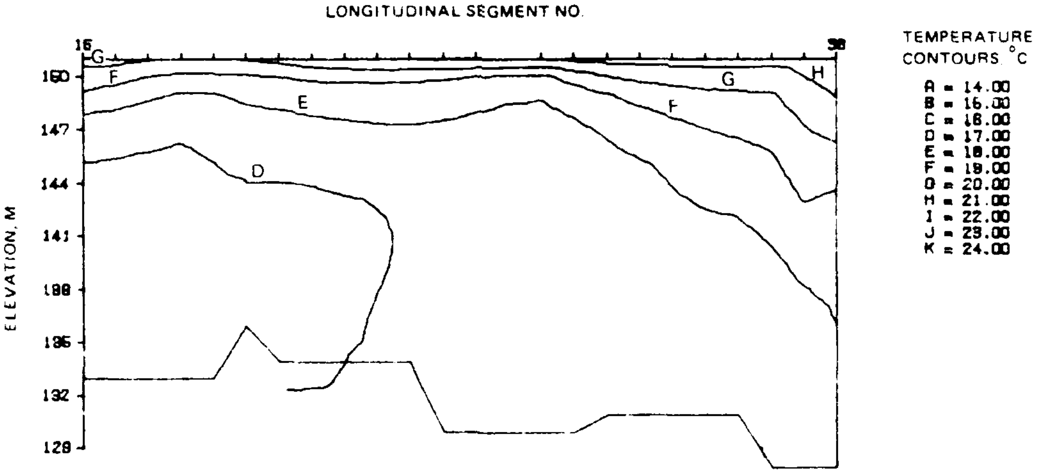


b. JULIAN DAY 214.75

DIURNAL EVALUATION RESULTS
TEMPERATURE CONTOURS
BRANCH 1
JULIAN DAYS 214.62 AND 214.75



a. JULIAN DAY 214.87



b. JULIAN DAY 215.00

DIURNAL EVALUATION RESULTS
TEMPERATURE CONTOURS
BRANCH 1
JULIAN DAYS 214.87 AND 215.00

APPENDIX A: BOUNDARY CONDITION INPUT DATA

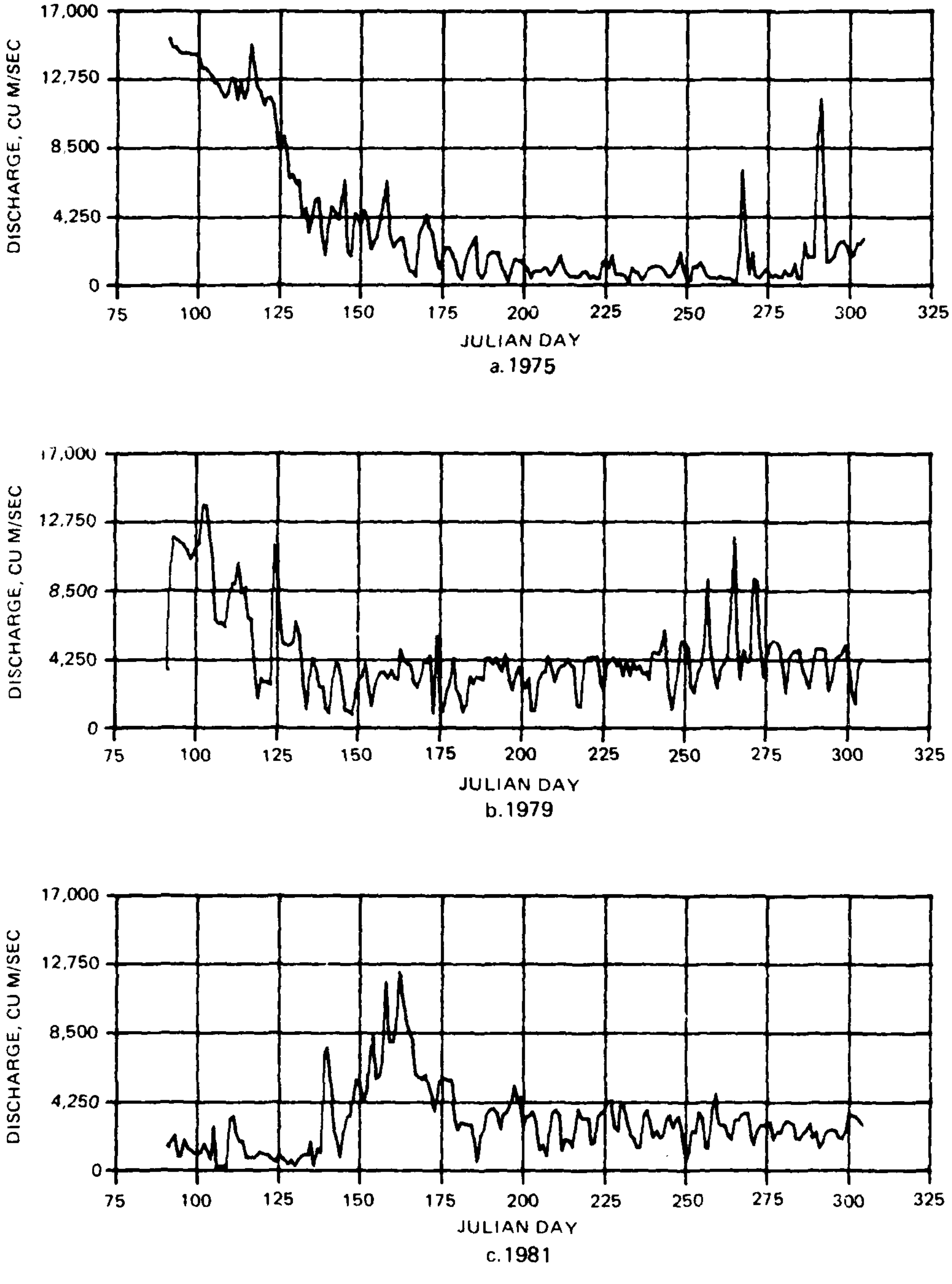
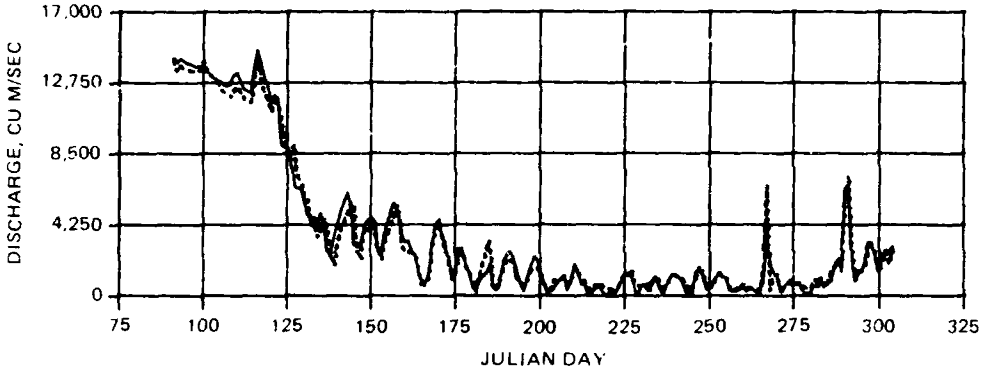
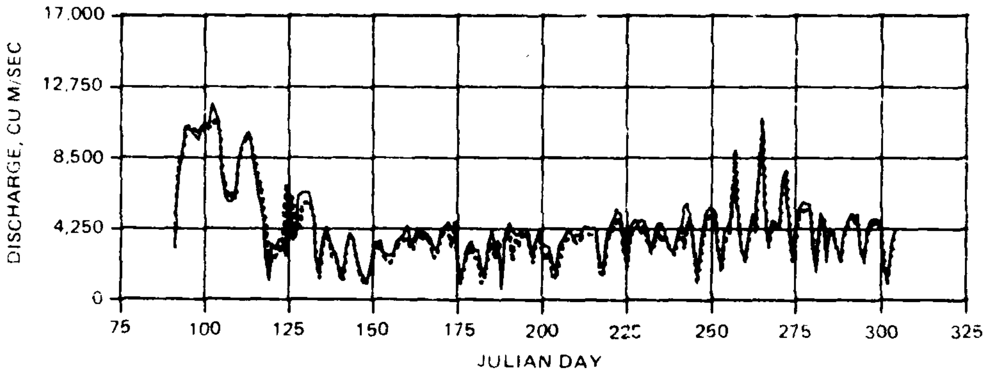


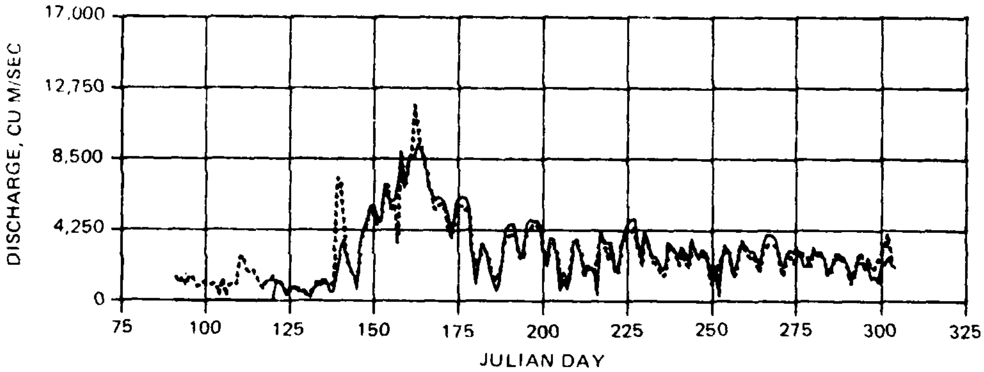
Figure A1. Discharge through Cordell Hull Lock and Dam



a. 1975



b. 1979



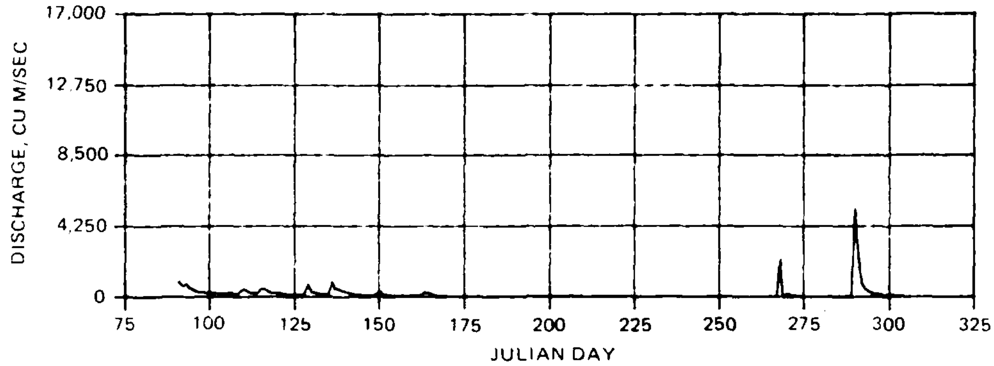
c. 1981

LEGEND

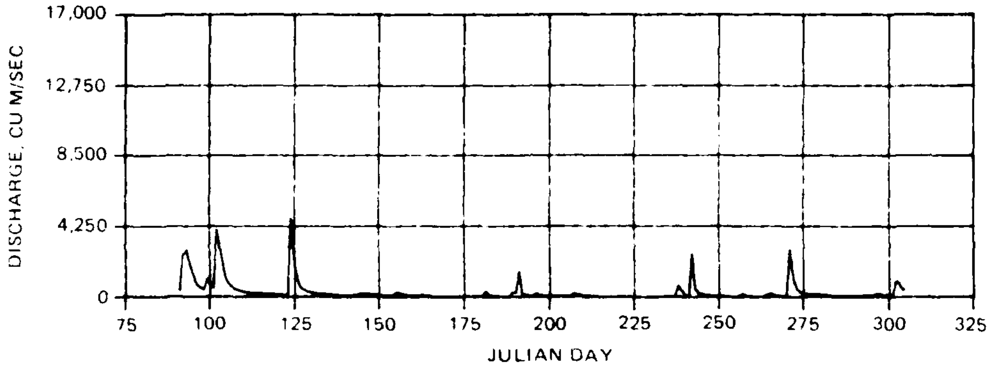
GAGED INFLOW

COMPUTED INFLOW

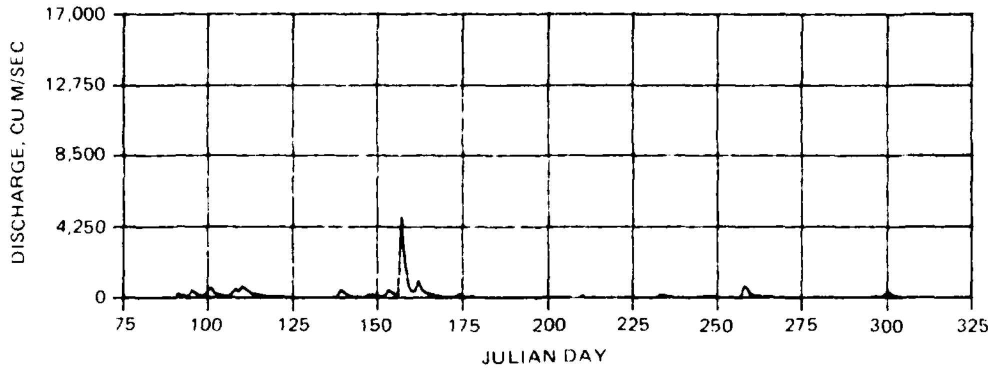
Figure A2. Gaged and computed inflow for the Cumberland River



a. 1975



b. 1979



c. 1981

Figure A3. Total inflow other than Cumberland River

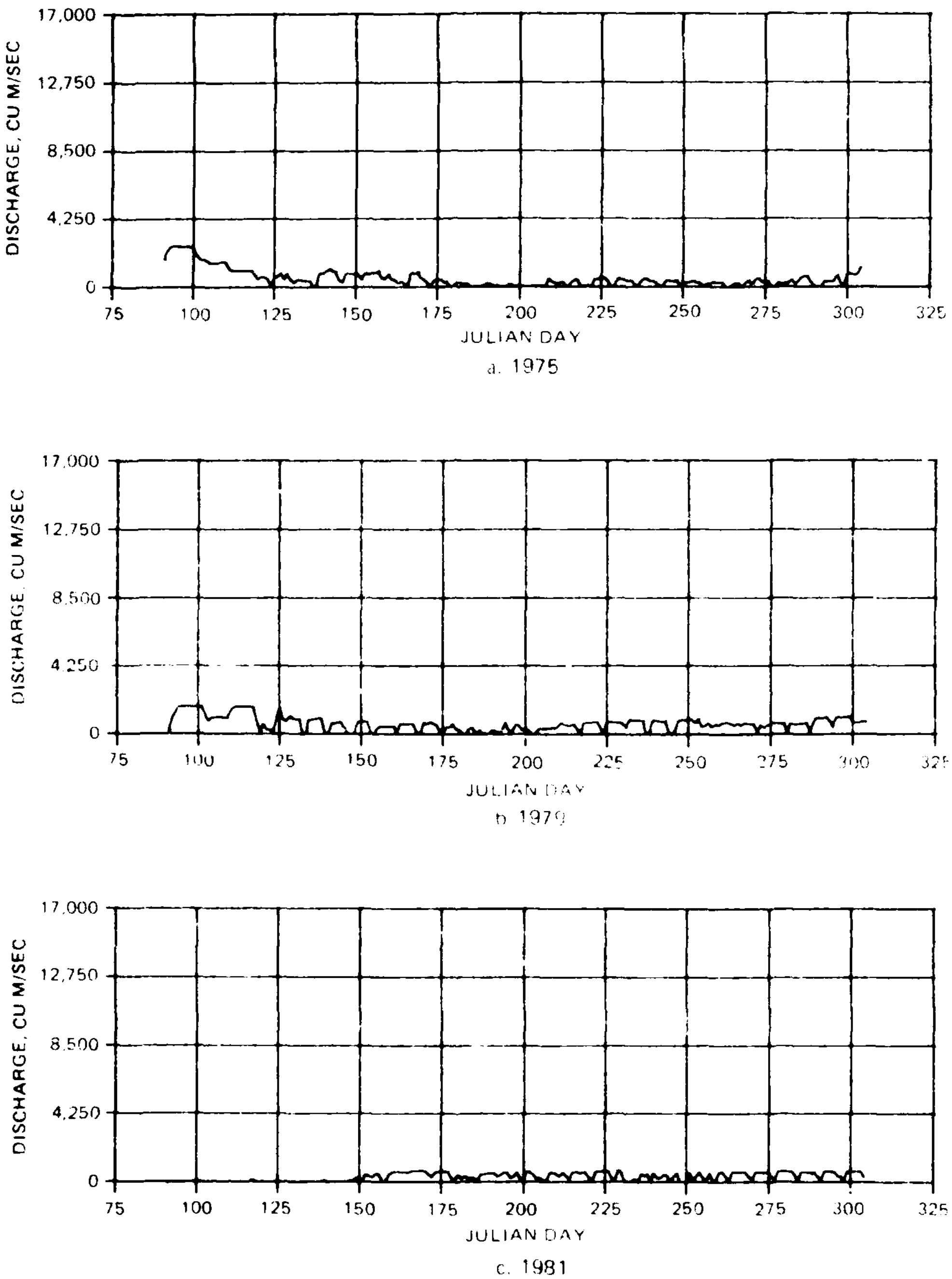


Figure A4. Obey River contribution to Cumberland River inflow

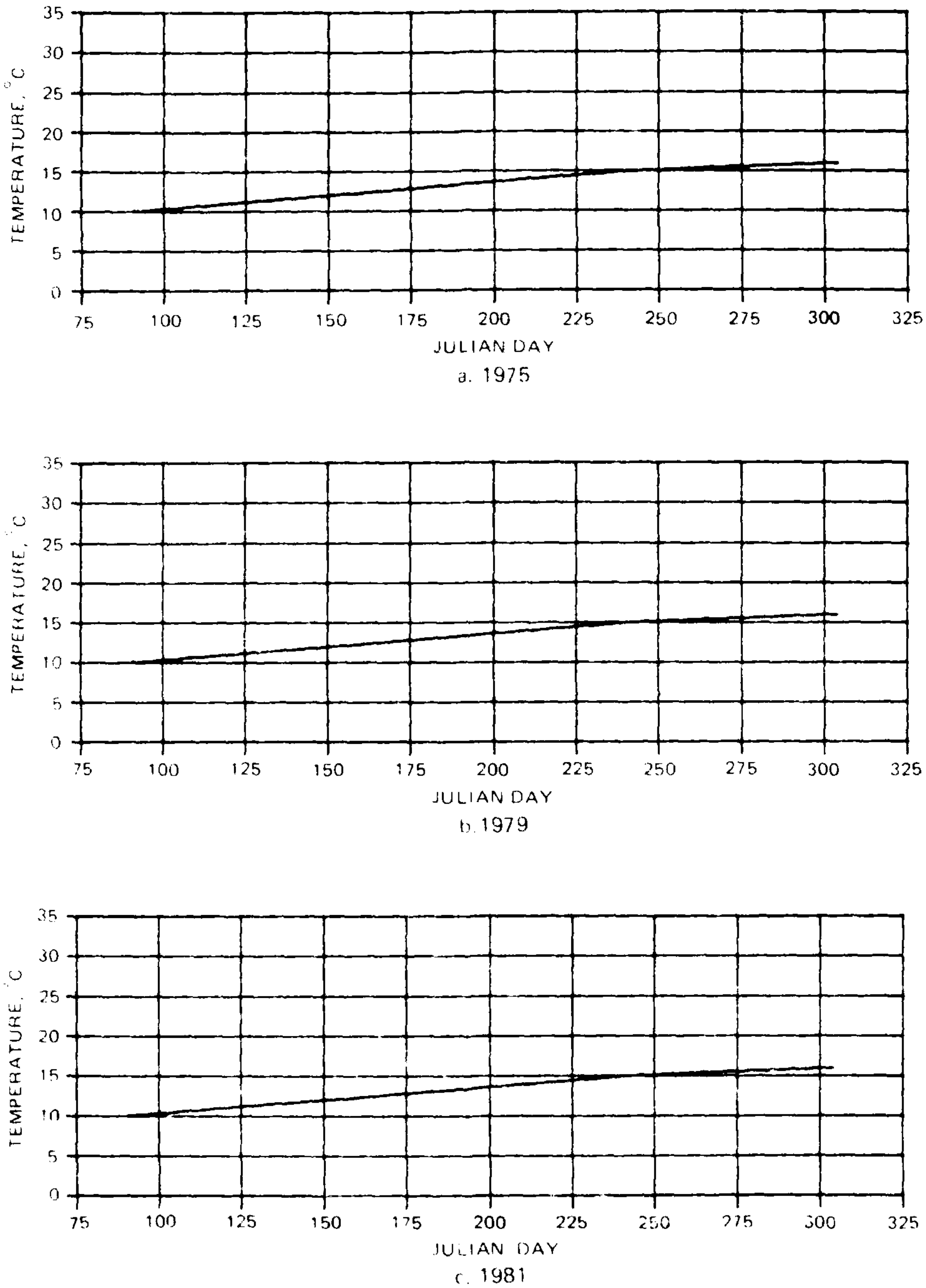


Figure A5. Inflow temperatures for Obey River contribution to the Cumberland River

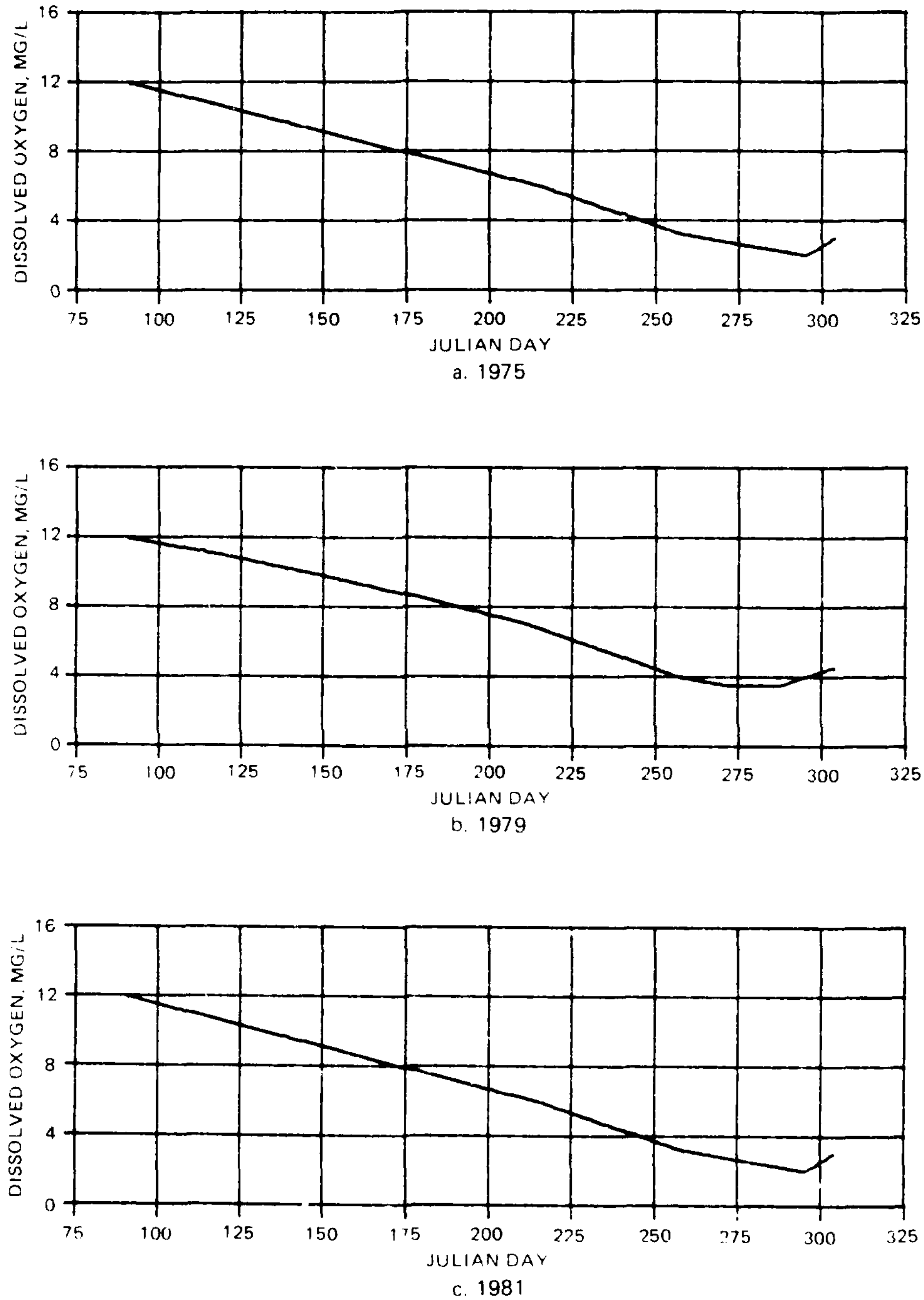


Figure A6. Inflow DO for Obey River contribution to the Cumberland River

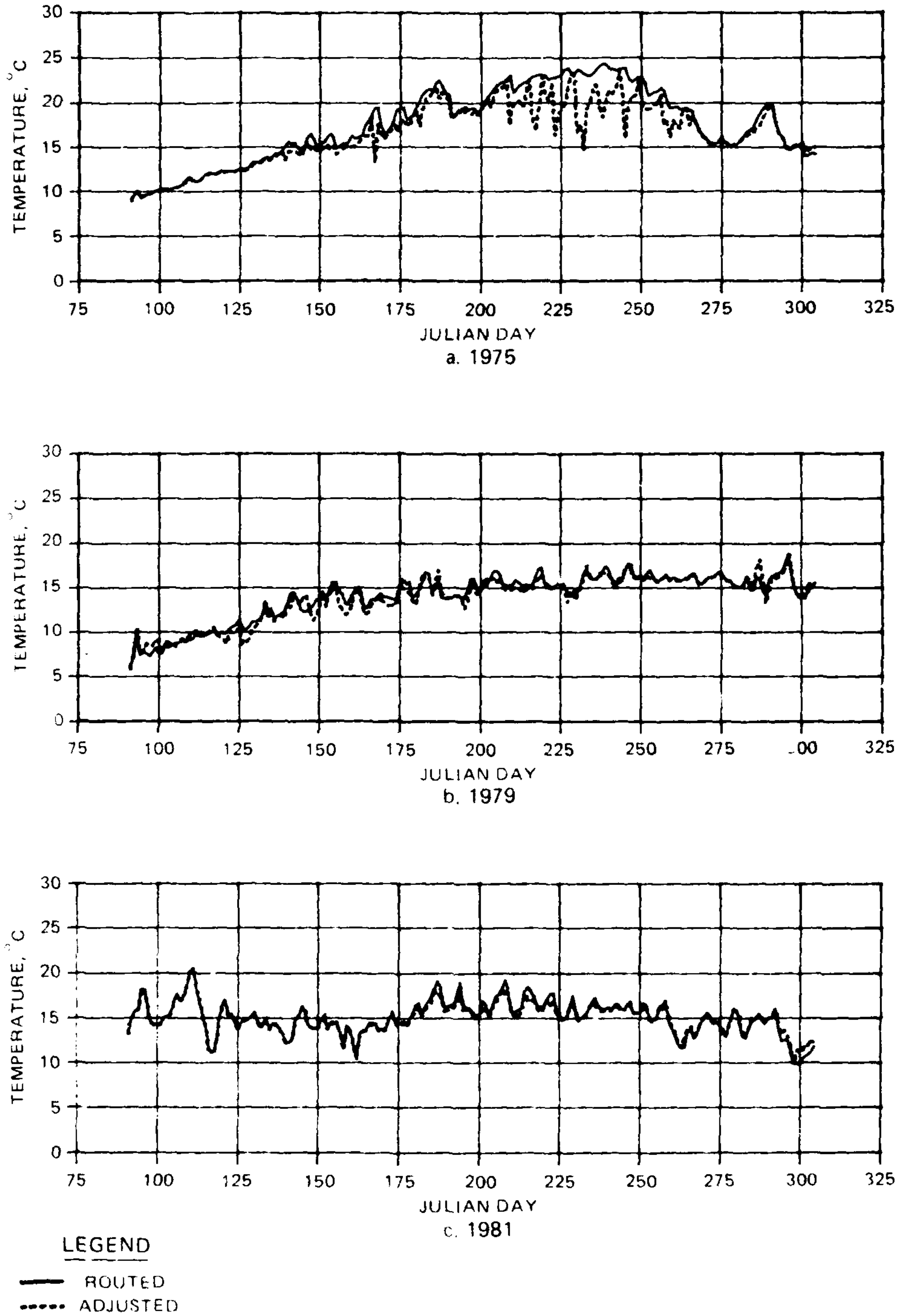


Figure A7. Nashville District-routed and adjusted inflow temperatures for Cumberland River

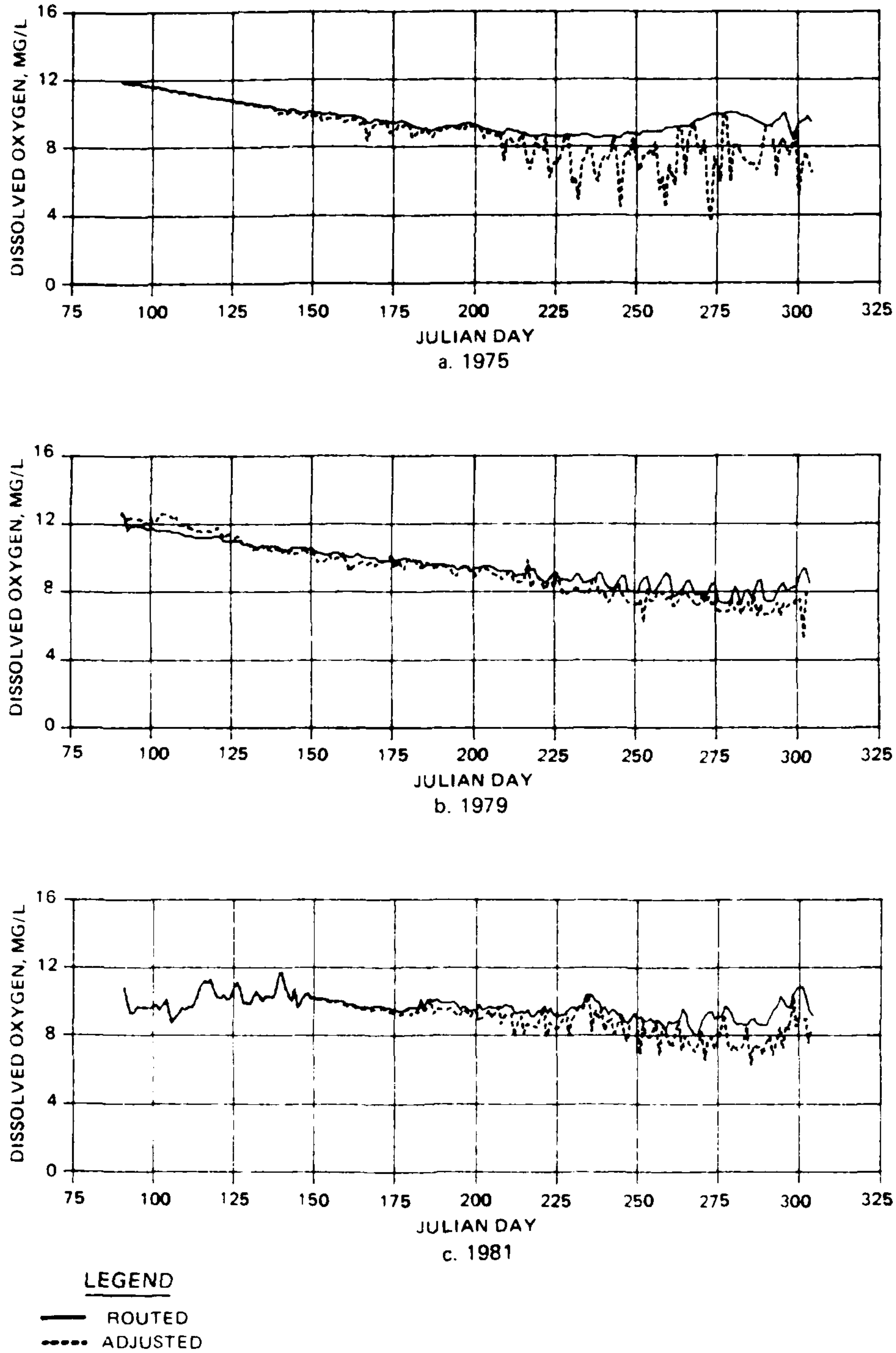
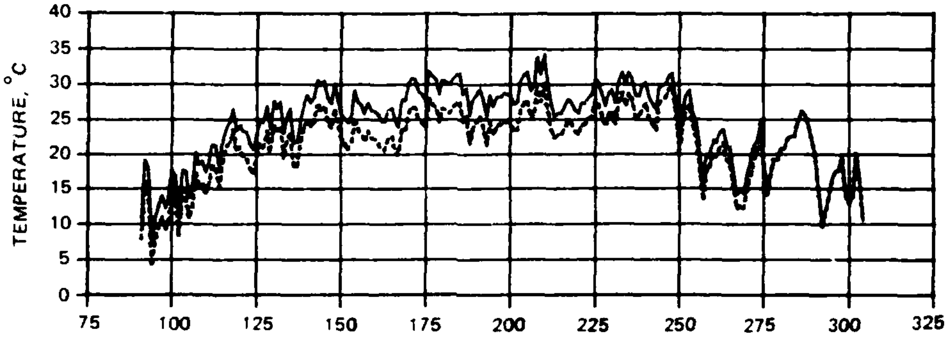
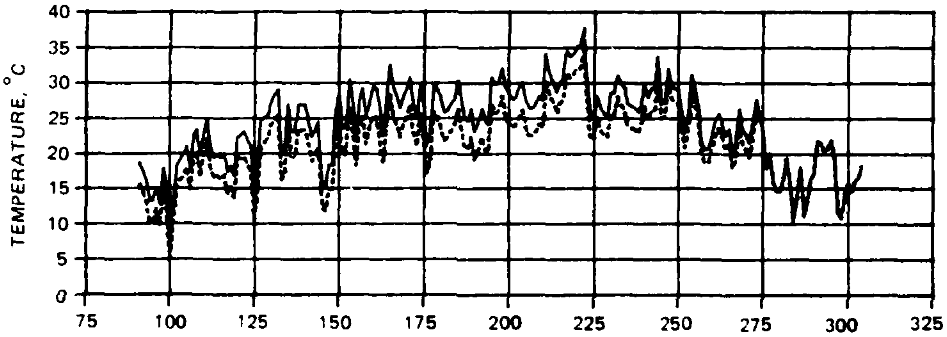


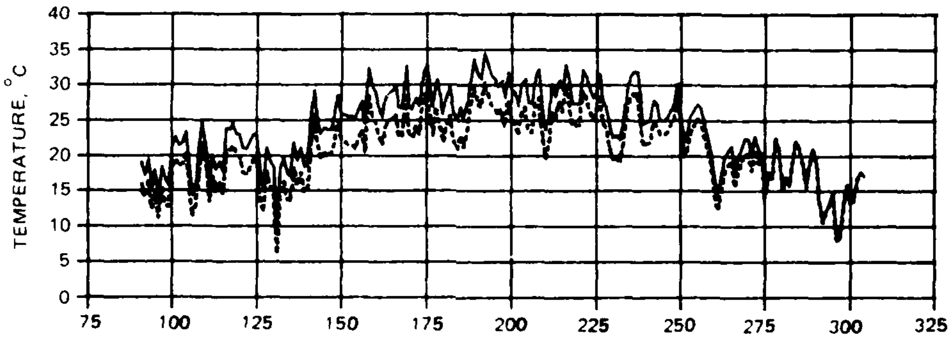
Figure A8. Nashville District-routed and adjusted inflow DO for the Cumberland River



a. 1975



b. 1979



c. 1981

LEGEND

—— NASHVILLE WEATHER STATION

----- ADJUSTED

Figure A9. Unadjusted and adjusted equilibrium temperatures

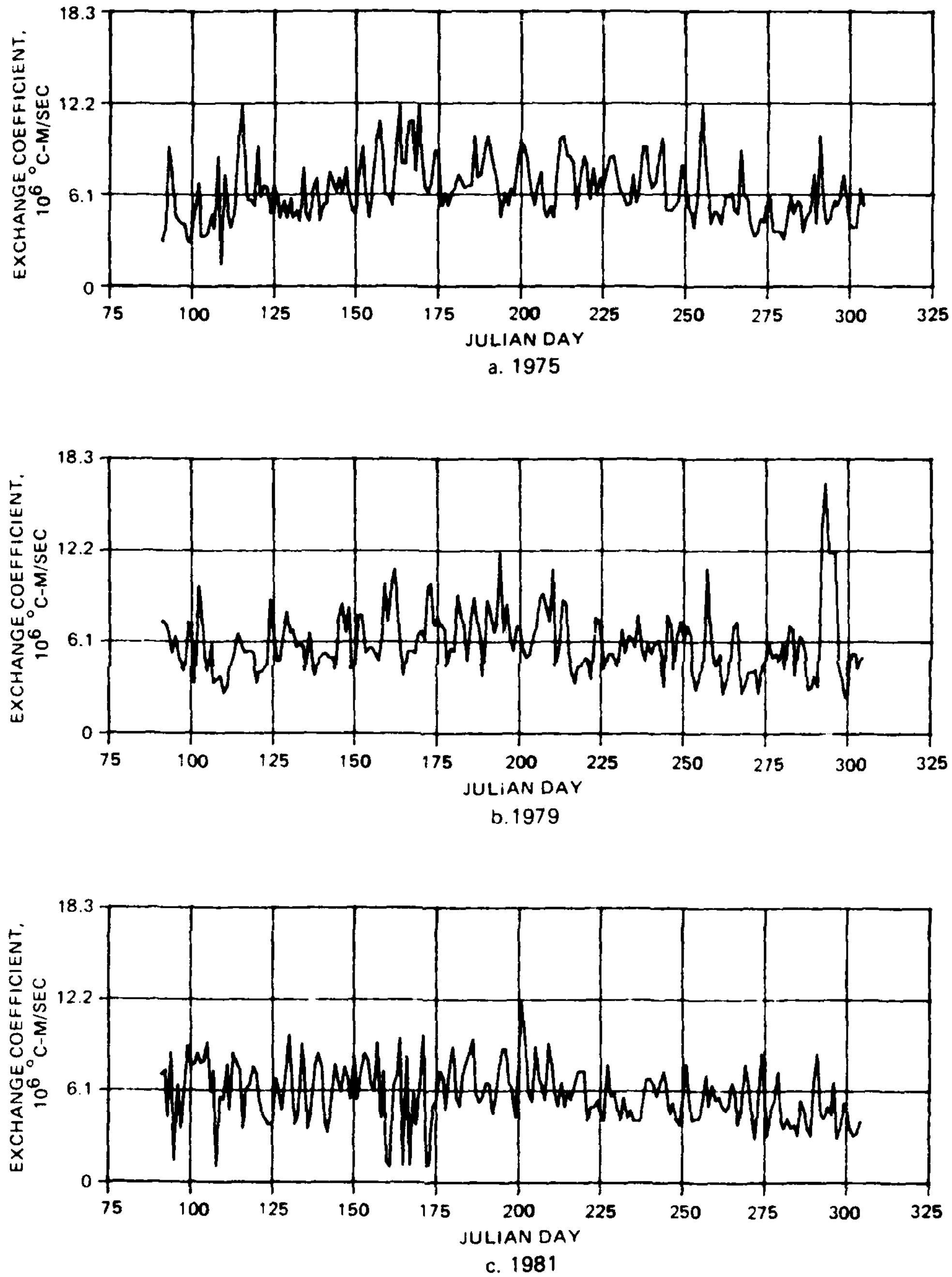


Figure A10. Coefficient of surface heat exchange

APPENDIX B: SENSITIVITY ANALYSIS

1. Early in the calibration phase of the study it became evident that the usual model adjustment coefficients for thermal energy distribution could not be manipulated to provide a good match between the observed data and predicted data. Therefore, an analysis of the impacts of various parameters on the reservoir's thermal patterns was initiated. The following parameters were investigated:

a. Solar radiation (SRO). The net shortwave input into the system.

b. Equilibrium temperature (ETM). Temperature at which the net rate of heat exchange between the water and the atmosphere is zero for given meteorological conditions.

c. Coefficient of surface heat exchange (CSHE). The rate of heat transfer across the air-water interface.

d. Longitudinal momentum diffusion coefficient (AX). The diffusion coefficient for momentum along the reservoir axis.

e. Longitudinal temperature diffusion coefficient (DXI). The diffusion coefficient for temperature along the reservoir axis.

f. Withdrawal description (QOUT(K)). Number and distribution of releases at the downstream boundary.

g. Inflow temperature (TIN). Temperature of the water entering the reservoir at the upstream boundary.

h. Initial temperature. Uniform temperature in field from which the computations are initiated.

2. These comparisons were made for a 30-day period in the late spring of 1979. This period was selected as a typical, seasonally high flow period. The high flow period was of particular interest as this reservoir is advectively dominated for much of the year. The short time span used for this evaluation (30 days) also means that seasonal impacts cannot be deduced from the results.

3. A "standard" simulation was performed by which the alternatives might be judged. The following parameters for the standard simulation were used:

AX = 1.0 sq m/sec

DXI = 1.0 sq m/sec

SRO = NORMAL

ETM = NORMAL

CSHE = NORMAL

INITIAL TEMPERATURE = 9.9° C

QOUT(K) = uniform velocity distribution from layers 5 through 26

These variables established the base condition for comparison. The NORMAL designation simply means that the daily averaged input values for this particular variable were not adjusted.

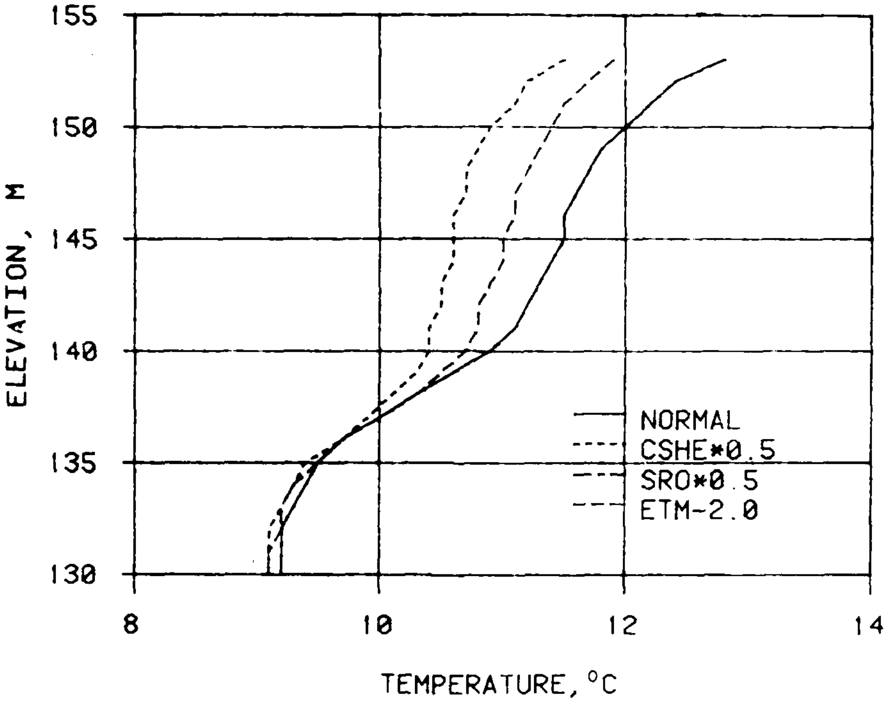


Figure B1. Meteorological evaluation

4. Figure B1 demonstrates the relative importance of the individual meteorological inputs. The curve for the adjusted solar radiation (SRO × 0.5) coincides with the base condition within 0.1° C. It can easily be seen that the thermal structure of the lake is much more sensitive to changes in the equilibrium temperature and the coefficient of surface heat exchange than to the shortwave radiative heat influx.

5. The reservoir is advectively dominated with coldwater inflow. Therefore, the difference between the equilibrium temperature and the surface water temperature tends to be large and is usually positive. From this evaluation, it can be reasoned from Equations B1 and B2 that if the overall shortwave radiative input is relatively small, no substantial changes to the thermal structure will be induced by the adjustment of β and γ .

$$H_s = \left[K(T_e - T_s) - (1 - \beta)\psi \right] \Delta x B \tag{B1}$$

$$H_i = (1 - \beta)\psi e^{-\gamma Z_i} \Delta x B_i \qquad (B2)$$

where

H_s = heat transfer into or out of the surface layer, °C-cu m/sec

K = coefficient of surface heat exchange, m/sec

T_e = equilibrium temperature, °C

T_s = surface temperature, °C

β = percentage of incoming solar radiation absorbed in the surface layer

ψ = shortwave radiation reaching the surface (SRO), °C-m/sec

Δx = segment length, m

B = segment width, m

H_i = heat absorption in layer i, °C-cu m/sec

e = mathematical constant (2.71828)

γ = attenuation coefficient, m^{-1}

Z_i = depth, m

B_i = width of segment i, m

6. The advective nature of the system also prevents large changes in

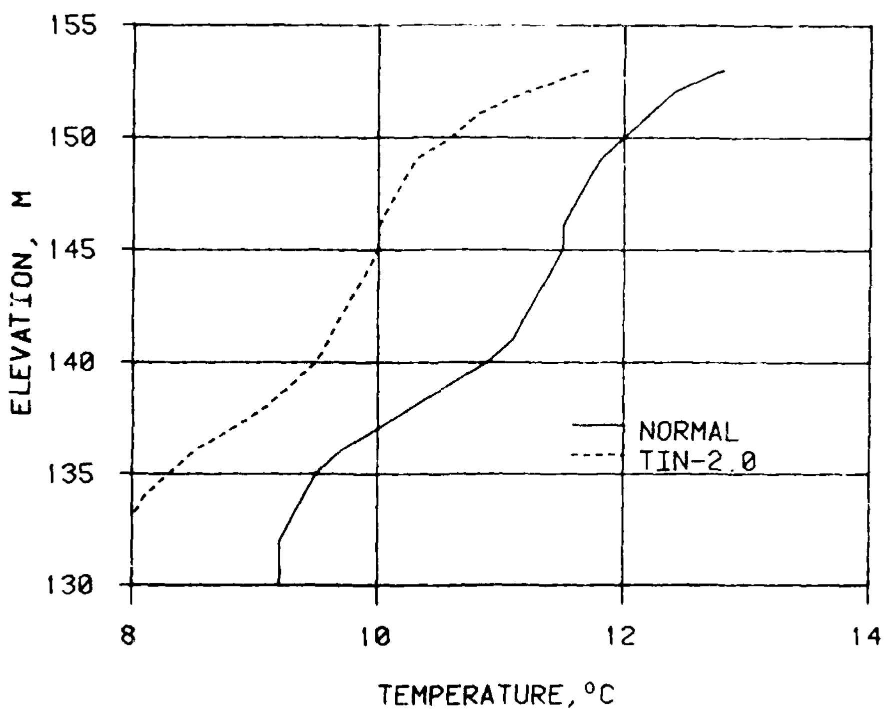


Figure B2. Inflow temperature evaluation the initial inflow quality during high flows as flow passes through the reservoir. Figure B2 demonstrates that a 2° C reduction in the inflow temperature resulted, for this period, in a greater than 1° C reduction over the entire water column near the outlet. Therefore, the water quality in the reservoir, even at the dam, is highly dependent on the inflow water quality.

7. The size of and flow distribution created by the outlets are also important considerations as seen in Figure B3. The ranges provided in the legend of Figure B3 represent the model layers over which the uniform velocity

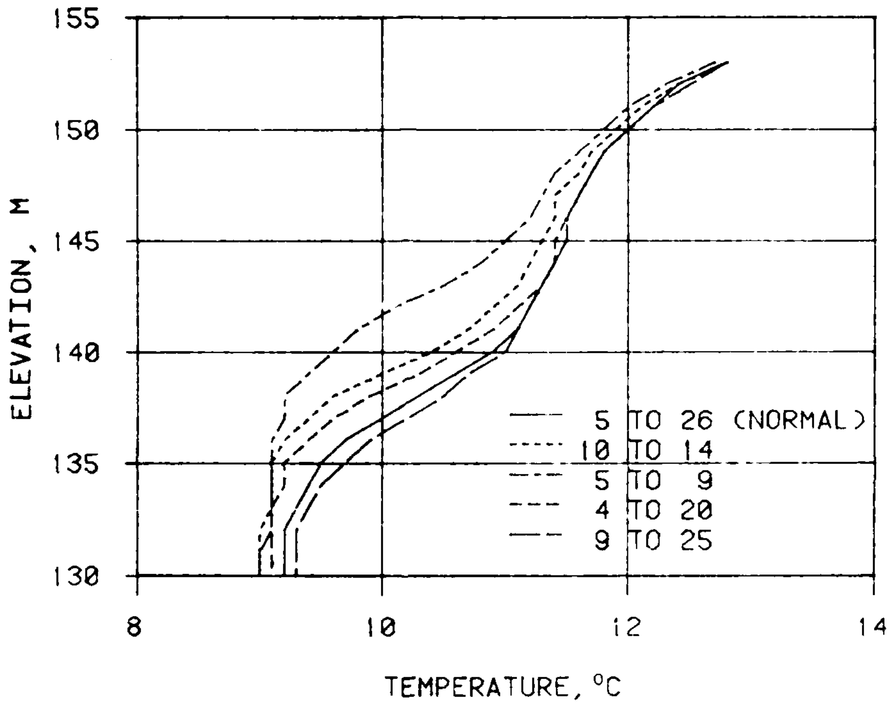


Figure B3. Outlet size comparison

distribution withdrawal was established at the downstream boundary. The location of the thermocline near the outlet is very dependent on vertical velocities near the structure which, in turn, are dictated by the outlet configuration. The temperatures at the bottom and at the surface appear to be less sensitive to the outlet configuration than those in the metalimnion, but over longer simulations, more substantial impacts might be attained. As expected, the high-level outlets produced a higher thermocline. This indicates that at least some influence on the stratification can be exerted by the selection of withdrawal descriptions.

8. The impacts of varying initial conditions were minimal for the

period evaluated. The base simulation began with a uniform temperature field of 9.9° C. Simulations were also performed with initial temperature fields of 5° and 13° C. Within 15 days, during this high flow period, the same temperature field was produced for all three simulations.

9. The diffusion coefficients for momentum and temperature were also found to be relatively unimportant during this period. The base condition employed values of 1.0 sq m/sec for both diffusion coefficients. Both were increased to 10.0 sq m/sec and the simulation performed again. The simulations produced the same temperature field within 0.1° C.

10. The parameters which showed the capability to significantly impact the thermal regime in this limited application were equilibrium temperature, coefficient of surface heat exchange, inflow temperature, and outflow distribution. Many of the traditional adjustment parameters in reservoir modeling exhibited little or no influence on the in-reservoir or release water qualities. This information can concentrate the adjustment effort on the parameters which may produce a significant improvement in the results.